Quantifying Spatial Structures Associated with Low-Severity Fire Regimes in the Eastern Cascade Mountains of Washington, USA

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Abstract

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Lara-Karena B. Kellogg

Co-chairs of the Supervisory Committee:
Professors David L. Peterson & Donald McKenzie
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Fire regimes are complex systems that represent an aggregate of spatial and temporal events whose statistical properties are scale-dependent. Despite the breadth of research regarding the spatial controls on fire regime variability, there are few datasets available with sufficient resolution to test spatially explicit hypotheses. I decomposed the spatial relationships within an extensive, spatially distributed network of geo-referenced, fire-scarred trees (17,700 scars) for six sites in eastern Washington. I utilized the spatial autocorrelation in fire history data to derive empirical and theoretical parameter estimates of semivariance that enabled us to infer mechanisms that generate spatial patterns of fire in ecosystems. I used the Mantel's test on time series of fire occurrence to differentiate the spatial component of their variability from the influences of environmental conditions.

The spatial dependence of historical fire regimes varied within and among sites. Spatial controls on low-severity fire regimes within similar dry forest ecosystem types operate at varying spatial scales, reflecting topographic properties of local landscapes. However, only portions of the spatial variability in fire events can be attributed to topography. In complex, rugged terrain, modal fire sizes associated with the effective ranges in variogram models were 150 ha or less, whereas in more open and rolling terrain, the spatial scale of fire occurrence was not controlled by landform. Results illustrate that the statistical spatial characteristics of fire regimes change with landform characteristics within a forest

type, suggesting that a simple relationship between fire frequency and forest-type does not exist. Quantifying the spatial structures in fire occurrence associated with topographic variation demonstrated that fire regime variability is scale and location dependent. By identifying the scale dependencies associated with specific fire regimes we can match the regime to the scales of the controlling factors with greater precision, thus increasing our abilities to evaluate their relationship.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table Number Page

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Introduction

Disturbance processes are typically scale dependent and may act across multiple scales of space and time simultaneously (Allen and Starr 1982; Pickett et al. 1989; Allen and Hoekstra 1991; Turner et al. 1989; Lertzman and Fall 1998; Turner et al. 2001). Fire is a critical disturbance process that contributes to ecological heterogeneity and maintains community structure and ecosystem function (White and Pickett 1985; Johnson 1992; Agee 1993; Miller and Urban 1999; Turner et al 2001). Large, severe fires over the last decade remind us that wildfire may perhaps be the single most important ecological disturbance in western North America. Forest managers are adopting practices utilizing wildfire and prescribed fire as a means of forest restoration to alleviate the adverse affects of fire exclusion, with priority given to forests with low-severity fire regimes (~25 million ha in the Western US). It will not be possible to restore that large an area and strategies for prioritizing will be needed. To integrate wildfire effectively in managed landscapes it will be imperative to identify the scales at which fire phenomena are relevant for individual ecosystem types in specific locations (Brown et al. 2004).

In fire history research considerable efforts have been made to assess the temporal variability associated with historic fire regimes. However, interaction of temporal and spatial patterns of fire regimes has even greater value. Fire history reconstructions have been used to analyze temporal variations in fire regimes and produce descriptive statistics defining fire frequencies for a given geographic location. Fire regimes are most often characterized within a specific geographic area and summarized by a statistic (e.g. mean fire return interval) reflecting the frequency of fire for the studied area (Agee 1993, Johnson and Gutsell 1994). There is no consensus on how fire regime statistics should be calculated because the mean and variance change over the time period and area of analysis (Baker 1989; Baker and Ehle 2001). Agreement on identifying the spatial and temporal characteristics of a fire regime has proven to be a difficult process (Falk 2004, McKenzie et al. in review).

Fire regimes are entrained in the interactions among climate, fuels and topography, each providing different influences at different temporal and spatial scales. The relative influences of the three controls can be classified as top-down or bottom-up (Lertzman and Fall 1998). Climate provides top-down controls on fire at large spatial scales whereas topography and fuels are typically viewed as bottom-up controls influencing fire at smaller scales.

Climate exerts top-down control on fire regimes throughout western North America at regional spatial scales, but with varying strength. Fire frequency in ponderosa pine (Pinus Ponderosa) forests in the American Southwest is strongly associated with El Nino Southern Oscillation (ENSO) cycles in the Southwest (Swetnam and Betancourt 1990; Veblen et al. 2000) whereas the relations in the mixed-conifer forests of the Northwest are less clear (Heyerdahl et al. 2001; Hessl et al. 2004; Wright and Agee 2004; Gedalof et al. in press). Conversely, fuels exert bottom-up influences on fire regimes at fine spatial scales, also with regional variation in strength. For example, fine-scale factors strongly influence fire regimes in Southwestern ponderosa pine forests by affecting fuel type, quantity and configuration (Schoennagel et al 2004). In similar forest types in the Northwest, fine-scale factors exert bottom-up controls on fire regimes theoretically by affecting fuel moisture (Tande 1979, Taylor and Skinner 1998, Heyerdahl et al 2001, Wright and Agee 2004). Climate and fuels are linked with topography as the common denominator which acts at meso-scales to mediate the interaction between the coarser and finer scale processes influencing fire regimes (Lertzman and Fall 1998).

Topographic gradients impose physical constraints on how ecological and physical processes interact to generate spatial patterns in dry forests of the western North America (Swanson et al. 1988). Topography contributes to the direct and indirect controls on fire behavior (Rothermel et al. 1972, 1983) and is considered to be the single most influential factor on fire regimes through its interactions with fuels and weather (Agee 1993, Lertzman 1998). The effects mediated by topography on historical fire regimes vary with spatial scale: local (tens of ha), intermediate (200 – 15,000 ha), and regional scales or greater (0.5 – 1.0 million ha, or greater) (Hemstrom and Franklin 1982; Swetnam and Baisan 1996; Taylor and Skinner 1998, Heyerdahl et al. 2001).

Controls on fire regimes at local scales are considered primarily a function of topographic position exerting a bottom-up control through variation in microclimates, thereby influencing the type, availability, abundance, continuity, and moisture of fuels (Romme and Knight 1981, 1982; Heyerdahl 2001; Beatty and Taylor 2001; Bekker and Taylor 2001; Taylor and Skinner 2003). Local topography directly and indirectly mediates the variability of fire regimes at intermediate scales, by modifying vegetation structure and composition, fuel continuity, and fuel moisture (Hemstrom and Franklin 1982; Taylor and Skinner 1998; Bekker and Skinner 2001; Heyerdahl et al. 2001; Taylor and Skinner 2003). Meso-scale topographic features may isolate patches of forest from major disturbance, potentially creating fire refugia (Camp et al. 1997, Agee 2000). For example, sub-drainages oriented perpendicular to prevailing winds may not burn even during large, high-intensity fires (Johnson and Larsen 1991).

The observed variation in fire regimes at regional scales or greater is more a function of climate than topography. Regional climatic variability appears to drive fire behavior and frequency (Agee 1993; Swetnam and Betancourt 1990; Swetnam 1993; Veblen et al. 2000; Heyerdahl 2001; Hessl et al. 2004; Gedalof et al. in press), although orographic controls are certainly important in mountainous regions. Regional-scale landforms may also affect fire extent directly by facilitating the spread of fire. For example, fire extent may be limited in regions with complex topography, which alters prevailing wind direction, and may be enabled in regions with gentle topography, which provides fewer barriers to fire spread (Swanson et al. 1988; Agee 1993; Swetnam and Baisan 1996).

Topographic variables are frequently mentioned as contributing to fire regime variability but are rarely identified uniquely or quantified as mechanisms that influence spatial patterns of fire occurrence. The inability to identify the extent to which topography is acting solely as a control on fire regime variability is confounded because topographic variables are often used as proxies for environmental variables. Issues of spatial-autocorrelation further confound our ability to make inferences regarding topography's contributions to fire regime variability (Legendre and Fortin 1989; Legendre and Legendre 1998). Fire history research typically begins in the field with measurements that are made at fine scales. From a statistical perspective, the sample data become increasingly spatially autocorrelated with finer-grained observations, meaning that the evidence of fires for one recorder tree is dependent upon the evidence of fire measured for nearby recorder trees (Dutilleul 1998). These data are often treated with standard parametric statistics, but violate the assumptions of independence (Dorner et al. 2003). It is also important to note that lack of evidence does not necessarily imply lack of fire.

Fire is a stochastic process in where each tree or group of trees that record fire represents a random sample drawn from a population that has an underlying probability distribution (Lertzman and Fall 1998; McKenzie and Hessl 2004; Falk 2004). Attempts to quantify the variability of fire regimes through fire history reconstructions have shown that many possible realizations exist; however, the underlying distributions may not be evident in a single analysis. Focusing on the properties of multiple fire events in space and time allows us to detect patterns that may not be discernable for individual fires. The underlying distribution is scale dependent because a fire regime is an aggregate of temporal events that overlap in space (Falk 2004). Quantifying scale dependencies will bring us closer to estimating the expected values of the population.

Statistical analysis of random processes allows us to model the spatial dependence associated with fire regimes. Several spatial and geo-statistical methods (spatial autocorrelation and the correlogram, semivariance and the variogram, and the Mantel's and partial Mantel's tests) have been applied to spatially explicit, autocorrelated data for the purpose of quantifying spatial dependence in ecology (Legendre and Troussellier 1988, Stephenson 1990, Wagner 2003), epidemiology (Cliff and Ord 1981), soil sciences (Isaaks and Srivastava 1989; Rossi et al. 1992), and genetics (Smouse et al. 1986, Oden and Sokal et al. 1992). To date, there have been no such analyses used to quantify the spatial structures associated with fire regimes.

My study utilized an extensive, spatially explicit, fire history dataset collected by Everett et al. (2000) to investigate the spatial variability of low-severity fire regimes associated with lower-elevation ponderosa pine forests in eastern Washington State. Spatial variability of the observed fire regimes was assessed on six study sites for spatial dependence using spatial and geo-statistical methods. I hypothesized that fire occurrence in each site would exhibit varying spatial structures with scale dependencies at short ranges in sites with complex terrain, and at longer ranges for areas with gentle terrain. The objectives of this study were to: quantify the topographic controls of fire occurrence at study area (global) and within study area (local) scales; determine if specific topographic/physiographic variables were driving spatial variability of fire occurrence; and identify the relative influences of top-down and bottom-up controls on the observed spatial dependencies.

Methods

Study area

Fire history data were collected by Everett et al. (2000) from six study sites located along a 300-km NE to SW distance from the Colville National Forest in the Okanogan Highlands in NE Washington to the east side of the Cascade Range to the Okanogan-Wenatchee National Forest in central Washington (figure 1). The study sites are located within forests historically dominated by ponderosa pine. East of the crest of the Cascade Mountains in Washington, USA forest ecosystems are characterized by mixed-conifer forest series, dominated by ponderosa pine at low and mid-elevations, and grand fir (*Abies grandis*) and Douglas-fir (*Pseudotsuga menziesii*) at mid- and upper elevations. Ponderosa pine, grand fir and Douglas-fir occupy a wide elevational range (Franklin and Dyrness 1988). These forest types are shaped by low, moderate, and high severity fire regimes (Agee 1993).

Fire history study sites

Everett et al. (2000) selected the study sites to capture the heterogeneity of the eastern Cascade landscape and the limited range of ponderosa pine-dominated ecosystems. The six sites and their locations from north to south are: South Deep and Quartzite located in the Colville National Forest, and Frosty Creek, Entiat, Swauk and Nile Creek located in the Okanogan-Wenatchee National Forest. The area of the study sites and sampling intensity varied at each site (Table 1).

The South Deep and Quartzite study areas are in the Colville National Forest (CNF) within the Okanogan Highlands. South Deep is within the southernmost range of the Selkirk Mountains. The mountainous environment is cool (mean annual temperature 7.2 degrees C, at 500 m elevation in Colville, WA, 48° 33’ N, 117° 54’ W, 1946-2001, Western Regional Climate Center 2003) and wet (75-100 cm yr -1, 1969-1990, Spatial Climate Analysis Service 2000) where ponderosa pine occurs in association with Douglas-fir, western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) in South Deep, and Douglas-fir and grand fir in Quartzite (Williams et al. 1995). Landform in both sites was heavily influenced by continental ice sheet glaciations producing rounded summits (elevations 500-2200 m), with relatively gentle mountain slopes (<20 deg.) separated by broad, U-shaped valleys. Both areas are covered with a mantle of till and outwash deposited over medium-to-coarse grain granitic bedrock (Schellhaas et al. 2000a and 2000b).

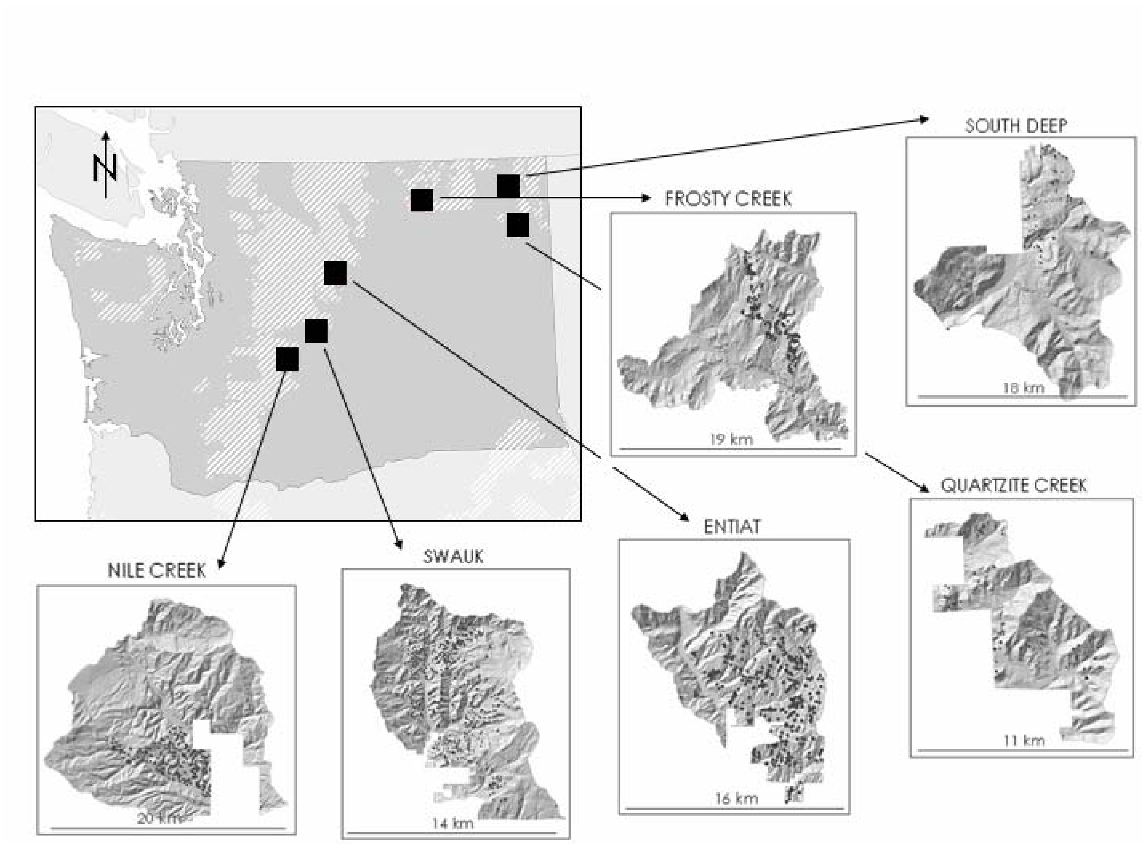


Figure 1 Fire history study sites, east of the crest of the Cascade Mountains, Washington, USA. From South to North: Nile, Swauk, Entiat, Frosty Creek, Quartzite and South Deep. The lined area in white shows the USDA Forest Service boundaries for the state of Washington.

The Frosty Creek, Entiat, Swauk and Nile study areas are located on the Okanogan-Wenatchee National Forest (OWNF). The OWNF spans three major ecological regions (Lillybridge et al. 1995). Frosty Creek and Entiat are located in "Chelan Terrain" (Alt and Hyndman 1984) that is comparatively warmer (8.3 degrees C at 265 m in Republic, WA, 48° 39' N, 118° 44' W, 1946-2001, Western Regional Climate Center 2003) than the Okanogan Highlands and drier (<30 cm yr -1, 1969-1990, Spatial Climate Analysis Service 2000) than the other four sites. Both study areas are dominated by forests of ponderosa pine and Douglas-fir (Lillybridge et al 1995), are mountainous, and were shaped by continental and mountain glaciations. Elevations in Frosty Creek range from 1000-1700 m, with summits that are barely discernable from the undulating U-shaped valleys. In contrast, topography in the Entiat is more complex and incised with deep (elevations 360-2000 m) V-shaped valleys (slopes 30-50 deg.). Geologically, both study areas are predominately granitic and metamorphic bedrock overlain with deposits of course volcanic ash and glacial till (Davis 1992; Lillybridge et al 1995; Schellhass et al. 2002).

Table 1. Location, area, sample sizes and analysis time frame of fire scarred trees at each of the six sites from south to north.

	Location			Fire Scars			
Site	Lat. (N)	Lon. (W)	Sampled area (ha)	Trees (n)	No. fire scars	First scar	Last scar
Nile	46° 52'	121° 05'	3237	234	2314	1367	1970
Swauk	47° 15'	120° 38'	11088	665	7048	1257	1942
Entiat	47° 48	120° 20'	12747	490	3904	1530	1988
Frosty Creek	48°34'	119°00'	2300	420	4461	1343	1994
Quartzite	48° 17'	117° 37'	3116	142	1300	1384	1989
South Deep	48° 45'	117° 40'	12019	168	680	1399	1986
Total			44507	2119	19707		

Table 2: Fire interval statistics (in years) for the period 1701-1900 defined as years in which 10% of trees recorded scars (minimum of 2 trees) (McKenzie et al. 2004).

Site	No. fire intervals	Mean interval	SD	Min interval	Max interval
Nile Creek	30	6	4	1	18
Swauk Creek	25	8	7	1	33
Entiat River	32	6	4	1	16
Frosty Creek	33	6	5	1	17
Quartzite	41	5	4	1	17
South Deep	20	10	9	1	31

The Swauk is located south of the “Chelan Terrain”, and extends from the Entiat fault to Ellensburg, Washington. This region is part of the old North Cascades subcontinent (Lillybridge et al. 1995); the Cascade mountains are narrower than average for the rest of the range and the climate is slightly warmer (9.8 degrees C at 323m in Yakima, WA, 46° 34’ N, 120° 32’ W, 1946-2001, Western Regional Climate Center 2003) and drier (100-150cm yr -1, 1969-1990, Spatial Climate Analysis Service 2000). Study areas are comprised of dry forest types, dominated by ponderosa pine, Douglas-fir, and grand fir (Lillybridge et al. 1995). The Swauk was outside of the limits of the continental ice sheet, but experienced extensive mountain glaciations (Lillybridge et al. 1995). Consequently, the topography is rugged with deeply incised mountains, and rocky ridges (elevations 400-3000 m) separated by V-shaped valleys with steep (30-60%) long slopes. The area has complex geological parent materials ranging from highly acidic granitic rock types to ultrabasic serpentine material, with extensive areas of marine sandstones (Williams and Lillybridge 1983; Williams et al. 1990; Lillybridge et al. 1995).

The Nile is the most southerly of the study areas and is located south of Ellensburg and north of the Yakima Reservation. Elevations are lower, but the climate and forest types in the Nile are comparable to those of the Swauk. Parent material is primarily comprised of basalt and andesite flows that have been subjected to extensive mountain glaciations (Lillybridge et al. 1995). Topography in the Nile is reflective of these events and its mountains terrain (600-2000 m) is characterized by long, gently sloping (10-30 deg.) ridges with steep dissected side slopes (20-50 deg).

Fire history data

Everett et al. (2000) generated an extensive, spatially distributed network of geo-referenced, crossdated fire-scar chronologies, ideal for spatial and temporal analyses of regional surface-fire history. The sampling design was focused on collecting samples by aspect. *Aspect polygons* were derived from topographic maps, then stratified into sub-polygons by combinations of aspect (northerly or southerly) and slope (flat, moderate, or steep) to ensure that fire scar samples were spatially segregated in the polygon. The samples were mainly collected from uplands and included few fire scars from low elevation riparian zones. Size of aspect polygons ranged from 32 to 1700 ha, and the number of aspect polygons within each watershed ranged from 2 to 21. For a complete description of the methodology see Everett et al. (2000) and Hessl et al. (2004).

Geographic data

Topographic variables were derived on a variable-by-variable basis from 30 m x 30 m resolution USGS digital elevation models (DEM). Each topographic attribute was extracted from the DEM using the GRID module of ESRI's ArcGis 8.2, and then saved to a single gridded data layer. Topographic data were used to model environmental conditions via GIS algorithms that calculate physiographic variables from DEM's. Algorithms used were: FLUX, (Kumar et al.

1997), which models the potential solar radiation received and "TRMI" (Parker 1982), which models potential topographic relative moisture index. FLUX estimates the short-wave solar radiation any cell receives over a period of time set by the user, correcting for season, latitude, and the shading that occurs from adjacent topographic features. TRMI calculates the potential soil moisture as a function of topographic variables, where indices range from 0 (xeric) to 60 (mesic).

Data analysis

Spatial and temporal dependence is an intrinsic part of many ecological processes (Cliff and Ord 1981, Rossi et al. 1992, Legendre and Legendre 1998). One of my goals in this project was to partition spatial dependence from the intrinsic variability associated with the fire regimes for the six study sites. Fire occurrence among sites was expected to show varying levels of spatial dependence, depending on geographic location and within-site topographic heterogeneity. Modeling spatial dependence is often accomplished using geostatistics under the theory of regionalized variables (Matheron 1965). One requirement of this approach is that of first- and second- order stationarity. This assumption is often violated with ecological data but can be circumvented by studying the differences between mean values Z(x) at separate distances (h) (equation 1), rather than the mean values themselves (Matheron 1965; Goovaerts 1997; and Webster and Oliver 2001),

Eq. 1) $$E\,[Z(x)-Z(x+h)] = 0)$$

and by replacing the covariance structure with a standardized variance of differences (equation 2) (Matheron 1965; Goovaerts 1997; and Webster and Oliver 2001).

Eq. 2) $E[\{Z(x)-Z(x+h)\}^2] = 2\gamma(h)$

Differences between mean fire return intervals across space, both for point mean fire return intervals and composite mean fire return intervals for aspect polygons were analyzed using the theory of regionalized variables. Because mean fire return intervals do not preserve temporal synchrony among points or composites, a time series of fire occurrence for each recorder tree in the fire history dataset was decomposed into binary (0,1) matrices by recorder tree or aspect polygon (columns) and the associated fire year (rows). Fire occurrence distance matrices were then created using Sorenson's measure of dissimilarity (equation 3):

Eq. 3) {1- [# of times both trees recorded fire /# of times at least one tree recorded fire]}

and consist of pairwise (Sorenson's) distances between all recorder trees in a sample. This measure was designed to eliminate years when there were no fires recorded in either of the trees in the comparison. The fire occurrence distance matrix was used as a multivariate response in the cluster analysis and Mantel tests.

Cluster analysis

Initial investigations were focused on using cluster analysis to generate hypotheses regarding the spatial patterns of historical fire occurrence, *sensu* Taylor and Skinner (2003), who used Ward's method of cluster analysis to identify spatial patterns and controls on historic fire regimes in the Klamath Mountains. Cluster analysis is a heuristic, statistical approach to identify homogeneous groups of observations, using a distance measure, but not appropriate for hypothesis testing (Sokal and Rolf 1995). A hierarchical agglomerative methodology was used to identify clusters of observations using the complete linkage method in S+ (Insightful 2000). Agglomerative techniques begin with single member clusters that are sequentially fused using the farthest pair of observations between two groups to determine the similarity of the two groups. This process is repeated until one large cluster is formed then a new cluster begins. This method was preferential, as it tends to produce very tight clusters of similar cases where the dissimilarity between two groups is equal to the greatest dissimilarity between a member of cluster *i* and a member of cluster *j*. The matrices used in the analysis were a Euclidean distance matrix and the fire occurrence matrix.

Geographic Information Systems

Synchronous temporal patterns of fire occurrence appeared to be spatially clustered, at least on some sites (figure 2). Fire scar locations were overlaid on the gridded-topographic and physiographic data layers to further explore the potential spatial variability. The variable value of each cell that contained a recorder tree location was extracted using Environmental Systems Research Institute's (ESRI) ARC module to assess the distributions of topographic and physiographic variables that coincide with fire occurrence. Environmental values were plotted in conditional plots to assess the overall environmental structure that coincided with the fire scar locations for each study area (figure 3).

I produced Topographic variance maps with ESRI's GRID module to accentuate dominant topographic features and locate areas where the environment was homogeneous vs. heterogeneous. The 'moving window' method in GRID was used to calculate focal descriptive statistics of the environment (terrain and physiography) on a variable-by-variable basis and built into single gridded data layers to identify each cell with a specific variance value. The first window used in the process was a 3 x 3 cell size and the standard deviation was calculated for the saved window as it moved systematically over the grid. I repeated this procedure on the 3 x 3 standard deviation map using a 10 x 10 cell-sized window, then used 10 x 10 standard deviation maps to calculate variance. The final maps of variance values were then used to produce environmental variability study area maps where the highest variance values are displayed as ridges. Fire occurrence data were then incorporated into the variance maps to compare patterns of topographic heterogeneity and the spatial extent of historically synchronous fire occurrence.

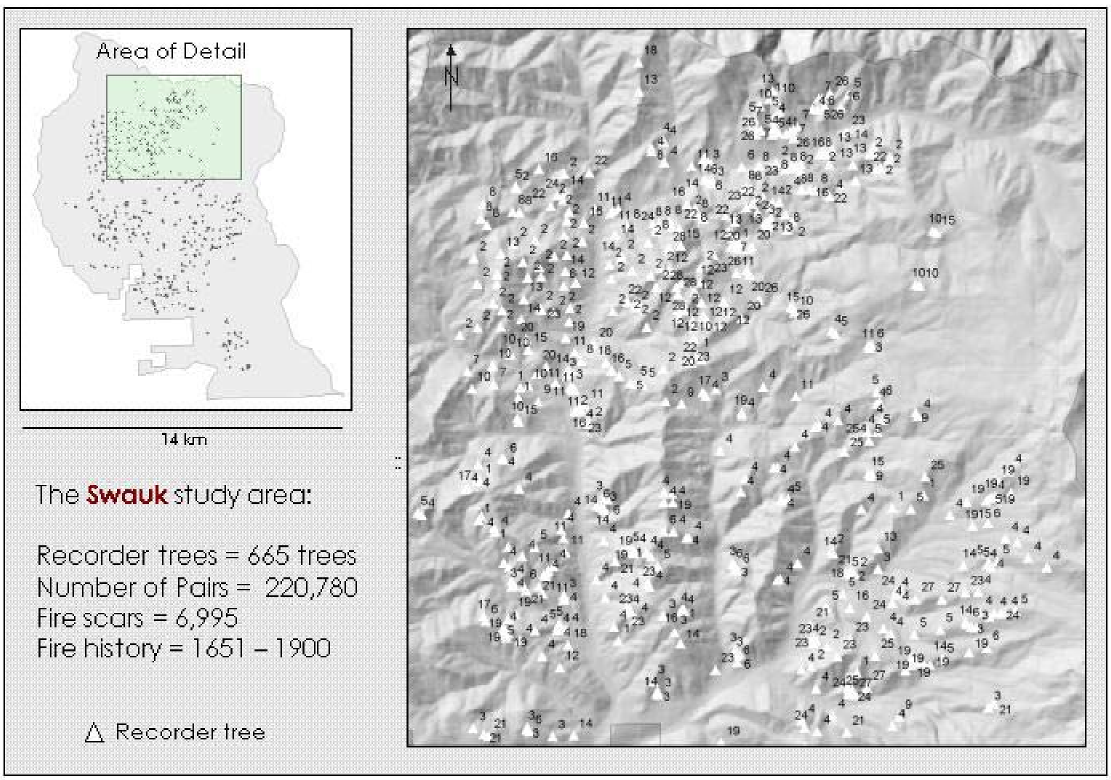


Figure 2 Hill-shaded digital elevation map of fire scar locations with cluster group identifications for the Swauk study area. Large groups (e.g. groups 2 and 4) appear spatially clustered.

To move beyond cluster analysis, I used the spatial database developed in GIS with alternative spatial analysis methods that were more appropriate for assessing significance.

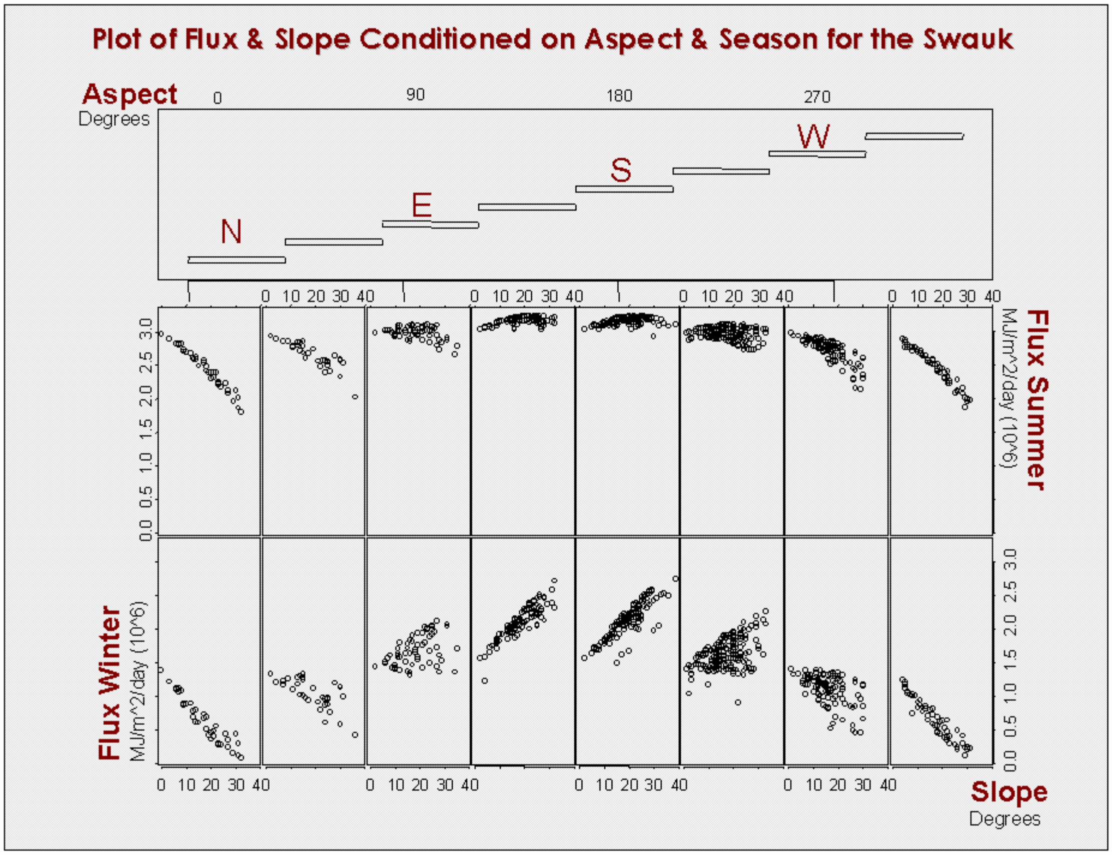


Figure 3 Conditional plot of winter and summer radiation relative to slope and aspect for fire scar locations in the Swauk study area. Each observation represents the observed environment of each 30m cell containing one or more fire scarred trees.

Spatial Analysis

Mantel's test

Mantel's tests were used to test the null hypothesis that temporal patterns of fire occurrence were spatially random in each study area. Mantel (1967) developed a method to evaluate the relationship between non-independent data and the associated spatial structure (Legendre and Fortin 1989; Fortin and Gurevitch 1993; Legendre and Legendre, 1998, Fortin and Payette 2002). The simple Mantel's test was applied to measure the correlation structure (r_m) between distance matrices, where the dependent matrix (y) is a measure of distance related to the observation (i.e. fire occurrence) and the independent matrix (x) is spatial dissimilarity (i.e. Euclidean distance, surface length distance, elevation differences) associated with locations of spatial observations. I chose to use the standardized form of the Mantel statistic, where the cross-product of the matrices (x,y) is standardized (Sx, Sy) and divided by the number of distances in the upper triangle of each matrix (d=[n(n-1)/2]), such that correlation coefficients are bounded on [-1, 1] (equation 4) (Legendre and Legendre 1998).

Significance of correlations (r_m) was evaluated via a restricted randomization procedure in which the rows (i) and columns (j) of the distance matrices (x,y) are randomly rearranged, and the correlation statistic is computed over a number of iterations to create a reference distribution (Fortin and Gurevitch 1993; Legendre and Legendre 1998, Fortin and Payette 2002).

Eq.4) Standardized Mantel's Test Statistic:

$$r_M = \frac{1}{d-1}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left[\frac{x_{ij}-\overline{x}}{s_x}\right]\left[\frac{y_{ij}-\overline{y}}{s_y}\right]$$

The fire occurrence matrix for each study area was used as the dependent variable and distance matrices (table 3) were used for each independent variable in the Mantel's test to differentiate the spatial component of the variability from the relationships between environmental conditions and spatial distributions of fire scarred trees. Correlations and 95% confidence intervals were calculated for each set of matrix comparisons. Significance was evaluated at a Bonferroni corrected alpha of: α = 0.05 / # of comparisons (Cliff and Ord 1981; Oden 1984).

Partial Mantel's test

When able to reject the null hypothesis that fire occurrence was spatially random in each study area, the partial Mantel's test was used to test if any single environmental variable could alone contribute a causal mechanism to the spatial patterns associated with the fire occurrence (Legendre 2000). Smouse et al. (1986) showed that the simple Mantel's could be extended to a multiple regression framework to compute partial Mantel's correlations to test the relationship among distance matrices. Partial Mantel's correlations quantify the contributions of each predictor variable for its partial effect on the spatial composition of the dependent variable. Correlations and 95% confidence intervals were calculated for each set of matrix comparisons. Significance was evaluated at a Bonferroni corrected alpha of: α = 0.05 / # simultaneous comparisons.

Table 3. Distance matrices used as dependent and independent variables for Mantel's Test.

Dependent variables	**Description of distance**
Fire occurrence	
Individual recorder trees	Proportion of times a recorder tree experienced fire relative to another tree (See cluster analysis)
Composite FRI aspect polygons	Absolute difference in aspect polygon composite fire return intervals
Independent variables	
Proximity (XY)	Euclidean distance
Proximity (aspect polygons)	Euclidian distance between nearest neighboring recorder trees in differing aspect polygons
Surface length distance	Euclidian distance incorporating the change in elevation over 20m increments of line segment
Elevation, slope, aspect, winter and summer solar radiation, and Topographic Relative Moisture Index	Absolute difference

Structure functions

The Mantel's test averages the correlation over the total area of the observations. When the fire scar locations were graphically displayed with topography and the clustered groups, it appeared that fire occurrence was structured at finer scales in study areas with complex topography. To determine if the variance was dependent upon the distance between observations, Moran's I (MI) and Semivariance (γ) were used to decompose the spatial variability of the observed variables among distance classes to detect finer scales and gradients of spatial dependence.

Moran's I was used to calculate the spatial-autocorrelation I(d) of fire return values for every pair of recorder trees(x_i, x_j) in the sample then standardized by their respective means (x_i, x_j) and multiplied by a weighted neighborhood distance matrix (W) and adjusted for sample size (n) to identify spatial patterns within the study areas (equation 5). Moran's I computes an index of covariance [-1,1] for a series of lag distances (or distance classes) from each pair of points in the sample (Legendre and Fortin 1989, Dutilleul 1998). Membership in a distance class was designated by assigning a weight (W) to each pair of points that were determined to be neighbors. Distances were calculated as Euclidean.

Eq. 5): Moran's I

$$I = \frac{n}{\sum_{i=1}^{i=n}\sum_{j=1}^{j=n} W_{ij}} \bullet \frac{\sum_{i=1}^{i=n}\sum_{j=1}^{j=n} W_{ij}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{\sum_{i=1}^{i=n}\left(x_i - \bar{x}\right)^2}$$

The computed values of I(d) were plotted in correlograms as a function of the distance classes (d), the null hypothesis being that the coefficient at each distance class is not significantly different from zero. Positive values of I(d) indicate positive autocorrelation, zero indicates complete randomness, and negative values indicate negative autocorrelation. The patterns of the correlograms were interpreted as suggesting spatial dependence if at least one of the Moran's I values was significant at the Bonferroni corrected level ($p<0.01$), and contained greater than 1% of the total possible pairs of points from the sample (Legendre and Fortin 1989).

To complement the Moran's I analysis I used the semivariance structure function to determine if additional scales of variability could be identified with direction (anisotropy) and distance (Euclidean) within the study areas. Semivariance ($\gamma(d)$) is a measure of the average degree of similarity (squared difference) between pairs of observations (y_h,y_i) as a function of distance and direction where membership to a distance class is determined by the sum of weights (W_{hi}) (equation 6) (Rossi et al. 1992). To calculate the semivariance the sum is divided by two times the number of points in each distance class (2**W**). Semivariance values are standardized covariance measures and range from [0, infinity], representing complete spatial dependence to complete spatial randomness.

Eq. 6) Semivariance

$$\gamma\left(d\right)=\frac{1}{2W}\sum_{h=1}^{n-1}\sum_{i=n+1}^{n}w_{hi}\left(y_h-y_i\right)^2$$

Empirical variograms were constructed as a function of Euclidean and surface length distances in varying azimuth directions (0, 45, 90, and 135 degrees with a 22.5 degree tolerance) for all variables. By confining the choice of theoretical variogram models to those functions which strictly observe monotonic change the parameters for the models can be predictive and used to make inferences from (see Goovaerts (1997); Legendre and Legendre (1998); and Webster and Oliver (2001)). Empirical variograms were then fit to one of the following four geo-statistical models for structure evaluation: random, linear, spherical, and wave/hole models (Legendre and Legendre 1998) using a weighted, non-linear least squares method (Cressie 1985). Equations used for geostatistical models are as follows:

Random: $\gamma(h)$ = mean variance

Linear: $\gamma(h) = C_o+C\,[(h/A_o)]$

Spherical: $\gamma(h) = C_o+C[1.5(h/A_o) – 0.5(h/A_o)^3]$, $h \leq A_o$

Wave/Hole: $\gamma(h) = C_o + C\{1-[\sin(A_o*h)*h/A_o)]\}$

where Co is the nugget variance; C is the asymptote of semivariance $\gamma(h)$; and Ao is the range.

The inferences made about the spatial patterns vary with the model used. The random model signifies a lack of spatial dependence (i.e., variance at a specific lag distance is not different from the mean sample variance). The remaining models (linear, spherical, wave/hole) imply spatial dependence and can be interpreted by their parameters in the theoretical variograms. The linear model is characterized by the slope (b) and infers a trend at a scale greater that the observed area. The spherical model and wave/hole models are characterized by the sill, nugget, and range. These parameters are used to identify local spatial dependence, where the sill is the sum of (c) and (c_o), corresponding to the value at which semivariance asymptotes to a flat line, and where the inflection point, if any, determines the range of spatial dependence for the data. The nugget (y-intercept) can be interpreted as local variation occurring at scales finer than the sampling area (non-zero intercept). The spherical model is used when variograms present low variance at short distances followed by increasing variance at greater distances. The hole/wave model is used when variogram exhibit a periodic structure with initial high values of semivariance at short distances.

Variogram patterns were considered robust for distance classes containing greater than 1% of the total possible pairs of points from the sample

(Legendre and Fortin 1989). Spatial dependence was assessed using a spatial dependence ratio (sill/(sill + nugget)) and, where dependence was directional, an anisotropy ratio (minor axis range/major axis range) was calculated. Both ratios are on scale of [0,1]; 0 indicating no relationship and 1 indicating a perfect relationship (Burgess and Webster 1980,1980b).

Results

Cluster analysis

The cluster analysis showed that fire occurrence was temporally clustered (synchronous fires for groups of recorder trees) for all six study areas using the hierarchical, complete linkage criterion. Under this criterion, the number of groups found within the study areas ranged from 15 to 28: Nile (15), Swauk (28), Entiat (24), Frosty Creek (21), Quartzite (18), and South Deep (17). The identification of groups suggests distinct spatial patterns of non-synchronous fire events occurring within the scale of the study area. Mean fire return intervals and lengths varied within the study areas.

Historical fire frequency for each clustered group was similar but non-synchronous and spatially segregated. Variation in fire occurrence synchronicity suggests consecutive fires burned varying portions of the study areas. However, lack of fire scars for certain years does not indicate that the fire did not burn in the location, but may suggest that fuels were altered by preceding fires or intensities were such that fires were not recorded (Taylor and Skinner 2003).

Environmental Variance Maps

Visual evaluation of the hierarchically clustered groups of fire occurrence and the gridded topographic/physiographic data across the six study areas suggested that fire occurrence was spatially structured relative to the amount of aggregate environmental variation at each site. When fire occurrence was spatially clustered, the aggregate variations in elevation, slope, and aspects were necessary to segregate or separate cluster groups (appendix C). I qualitatively ranked the study areas on a continuum from gentle to complex terrain based on the amount of overlapping, highly variable environment present in the variance maps of the sampled areas. The sites, gentle to complex, are: Frosty Creek, Quartzite, Nile, South Deep, Entiat, and Swauk.

Mantel's Test

The first null hypothesis tested with the Mantel's test was that there was no relationship between temporal patterns of fire occurrence at points and the geographic distances between them. The null hypothesis was rejected ($p<0.01$, Bonferroni corrected) in all cases leading to the conclusion that there were varying levels of spatial correlation associated with fire occurrence in all six study sites. Both Euclidean and surface length were good predictors of fire occurrence, but showed no significant difference in correlation values (table 4). The strongest, global-spatial dependence (study area scale) was seen in the Nile and Swauk ($r = 0.50$, and 0.54) with moderate dependence present in the Entiat and Frosty Creek ($r = 0.34$, and 0.35) and weaker dependence in the Quartzite and South Deep ($r = 0.29$, and 0.19).

The second null hypothesis tested was that there was no relationship between fire occurrence and individual environmental variables. The individual topographic variables (elevation, slope and aspect) and modeled physiographic variables (FLUX, winter and summer solar radiation and TRMI, topographic relative moisture index), individual variable correlations were predominantly weak ($r< 0.10$) and insignificant ($p>0.5$), except for the Nile where elevation was significantly ($p<0.01$) structured ($r = 0.269$) with fire occurrence (Table 5).

Table 4 Correlation values from simple Mantel's test between fire occurrence and geographic distances, where ** indicates p<0.01. Study areas are listed from south to north.

			Confidence Intervals for Euclidean Distance	
	Independent Matrices		Lower Limit	Upper Limit
Site	**Euclidian**	**Surface Length**	**(2.5%)**	**(97.5%)**
NILE	0.500**	0.501**	0.482	0.517
SWAUK	0.540**	0.541**	0.534	0.547
ENTIAT	0.342**	0.342**	0.330	0.355
FROSTY CREEK	0.346**	0.326**	0.332	0.363
QUARTZITE	0.195**	0.195**	0.177	0.219
SOUTH DEEP	0.295**	0.293**	0.270	0.324

I failed to reject the null hypothesis for all other sites, including sites with significant (p<0.01) but weak (r<0.1) correlations and concluded that no individual variable alone explained fire regime variability except for elevation in the Nile. The partial Mantel's test confirmed that no individual environmental variable contributed a partial effect on the spatial composition of fire synchrony for any of the study sites (appendix B).

Table 5 Correlation values from simple Mantel's test between fire occurrence and topographic and physiographic measures, where ** indicates p<0.01 and, * indicates p<0.05. FLUX.W and FLUX.S are winter and summer solar radiation measured in Mj/m^2 per day and TRMI is the topographic relative moisture index.

SITE~	ELEVATION	SLOPE	ASPECT	FLUX.W	FLUX.S	TRMI
NILE	0.269**	0.005	-0.067	-0.018	-0.030	0.010
SWAUK	-0.029	-0.005	0.024	0.018	-0.030	0.016
ENTIAT	0.068	0.036	0.024	0.046	0.039	0.008
FROSTY CREEK	-0.002	-0.006	0.056**	0.014	0.008	0.011
QUARTZITE	0.076**	0.011	0.010	0.009	0.015	0.003
SOUTH DEEP	0.031	-0.030	0.049*	0.008	-0.002	0.063**

The null hypothesis tested was that there was no relationship between fire frequency and aspect. In all sites except the Entiat, test statistics show that the composite fire return intervals (CFRI) by aspect polygon vary independently aspect to aspect with weak correlations (r<0.15, p>0.05), suggesting that fire frequencies among adjacent aspect polygons were not correlated. CFRI in the Entiat were significantly (p<0.01) and moderately structured (r = 0.226) with proximity, suggesting that fire frequency was more similar in adjacent polygons (full results in Appendix B).

Structure Functions

Moran's I Spatial Autocorrelation

Moran's I (I(d)) was calculated for mean fire return intervals in 50 m increments to a maximum distance (less than one-half the total distance across the study areas) of 10km. Moran's I correlograms were only globally significant ($p<0.01$) for the Swauk and Nile study areas where they exhibited similar patterns of exponential decay from a maximum correlation at the shortest distances ($d<100$ m) to a minimum correlation as distance increased. In the Swauk I(d) decreased from 0.5 to -0.2, and in the Nile I(d) decreased from 0.4 to -1.0 (figure 4). This pattern suggests that measures of MFRI are spatially structured at regular 50 m intervals where structure decays with distance, to a range of 5 km in the Swauk and 3.4 km in the Nile. The lack of significant spatial autocorrelation for MFRI in the Quartzite, South Deep, Frosty Creek and Entiat study areas suggests sampled points are spatially independent with respect to fire frequency. Moran's I (I(d)) was also calculated for CFRI by aspect polygon in 50m increments to a maximum of 10 km. These correlograms were insignificant and patterns showed the composite fire return intervals vary independently from aspect polygon to aspect polygon in all study areas.

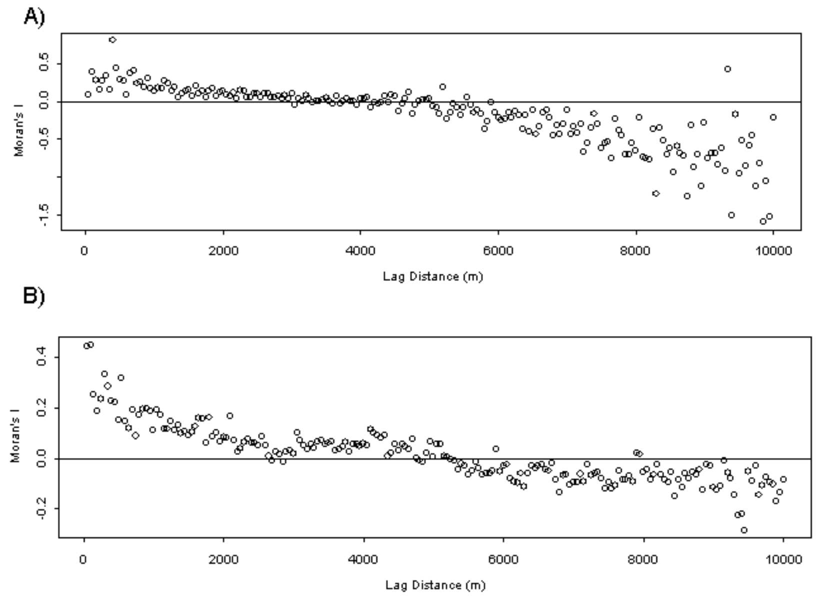


Figure 4 Correlograms of Moran' I measures of mean fire return intervals as a function of distance (m) in the A) Nile and B) Swauk study areas.

Variogram results

MFRI

Theoretical models of semivariance for MFRI in all six sites exhibited varying ranges of spatial dependence. Empirical variograms fit a spherical model for the Swauk, Entiat and South Deep and a wave/hole model for the Nile (figures 6-8). Topography was highly complex and dissected in the Swauk and Entiat, but gentle in the South Deep. Random models were appropriate for both Frosty Creek and Quartzite owing to the lack of fit of the other models. Topography is gentle in both Frosty Creek and South Deep.

The omni-directional variograms of MFRI in the Swauk, Entiat and South Deep exhibited a locally constrained, monotonically increasing spatial dependence and were fit to spherical models. Theoretical variogram models indicated that historical fire regimes exhibited local spatial dependence in the Swauk (54% of variance explained), Entiat (41% of variance explained), and South Deep (26% of variance explained), but did not in the Nile, Frosty Creek, and Quartzite. The range parameter from the spherical model showed that spatial structures were such that fire frequency was synchronous for long distances (< 3.8 km) in the South Deep and for shorter distances in the Entiat (<784 m) and the Swauk (<366 m). The effective range for these sites can be interpreted as a modal area of influence where fire burned with the same frequency, and possibly synchronously; approximately 40 ha in the Swauk, 180 ha in the Entiat, and 4300 ha in South Deep. Semivariance decomposed over direction showed MFRIs were anisotropic (Table 5), meaning the variance changed with direction, although there was no detectable anisotropy in the NW-SE direction for both the Entiat and South Deep. Measures of anisotropy and effective directional ranges for the three spherical models were varied (figures 5a-c). Directional ranges can be interpreted, in the same manner, to represent an area of influence, or of homogeneous fire frequency.

Table 5 Spherical model parameters showing effective ranges and measures of anisotropy for sites with spatially dependent fire frequencies.

Site	Effective Range (m)	Anisotropy Ratio (%)	Range Major Axis (m), Direction	Range Minor Axis (m), Direction
Swauk	366	27	364-SWNE	171-NWSE
Entiat	784	37	1245-NS	458-SWNE
South Deep	3788	57	7260-EW	2958-SWNE

Semivariance for the Swauk study area was calculated every 50 m to a maximum of 5km. The maximum and mean distances between any two pairs of points were equal to 18 km and 5.5 km respectively. The minimum number of pairs compared was 172, the mean 975, and the maximum was 1352. Semivariance for the Entiat was calculated every 50 m to a maximum of 5 km. where the minimum number of pairs compared at any distance was 79, the mean was 490 and the maximum was 742. Semivariance for the South Deep study area was calculated every 50m to a maximum of 9km, where the minimum number of pairs compared at any distance was 29, the mean was 65 and the maximum was 111.

Semivariance for the Nile study area was calculated every 200 m to a maximum of 5km where the mean distance was 3.5 km and the maximum distance was 10.9 km and the minimum number of pairs compared was 52, the mean 432 and the maximum was 615 Local spatial dependence in the Nile differed from the other areas, where empirical data were best fit by the wave/hole model. The maximum sample semivariance observed in the Nile occurred at short distances (< 400 m) where dissimilarity decayed to similar semivariance values for distances less than 1km, implying that fire frequency is highly variable at distances less than 1km. In some instance when empirical variograms have this concave upward form (fig. 6), the decreasing gradient may be a indicative of a local trend or drift (product of sampling design) and constitute a random process (Webster and Oliver 2001).

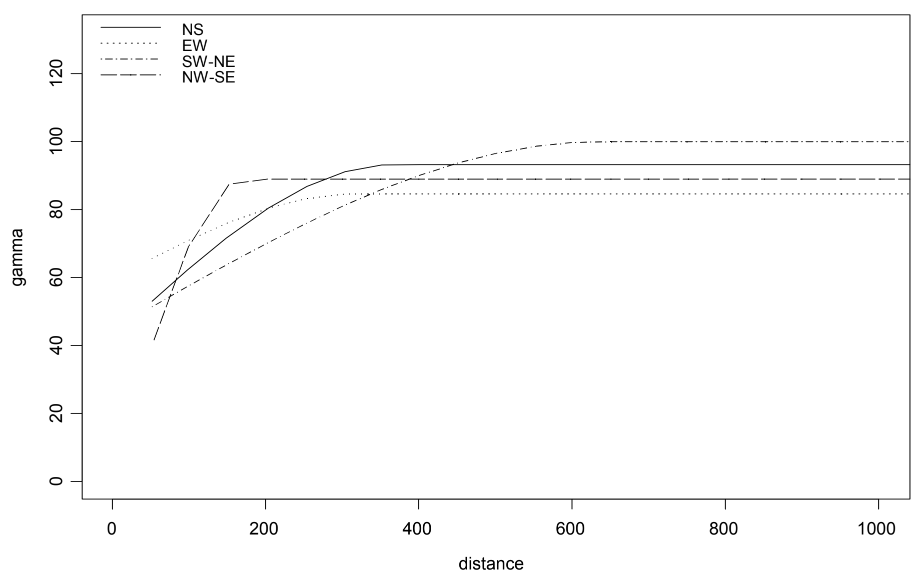


Figure 5a Theoretical-directional variograms (spherical model) of Semivariance in the Swauk

Semivariance for the Frosty Creek and Quartzite study areas was calculated every 50 m to a maximum of 5 km where the minimum number of pairs compared in Frosty Creek was 13, the mean 426 and the maximum was 566 and in Quartzite the minimum number of pairs compared was 7, the mean 14 and the maximum was 40. Mean sample semivariance was observed at all distances in empirical variograms suggesting that the spatial variability is random (figure 7). However, in Quartzite, when semivariance was decomposed over direction, semivariance monotonically increased with anisotropy detectable (71% anisotropy) in the NW-SE and EW directions with ranges equal to 1189 m and 851 m, respectively. No spatial dependence was present in the SW-NE or NS directions. In Frosty Creek, spatial variability remained random when semivariance was decomposed over direction (Results in appendix A)

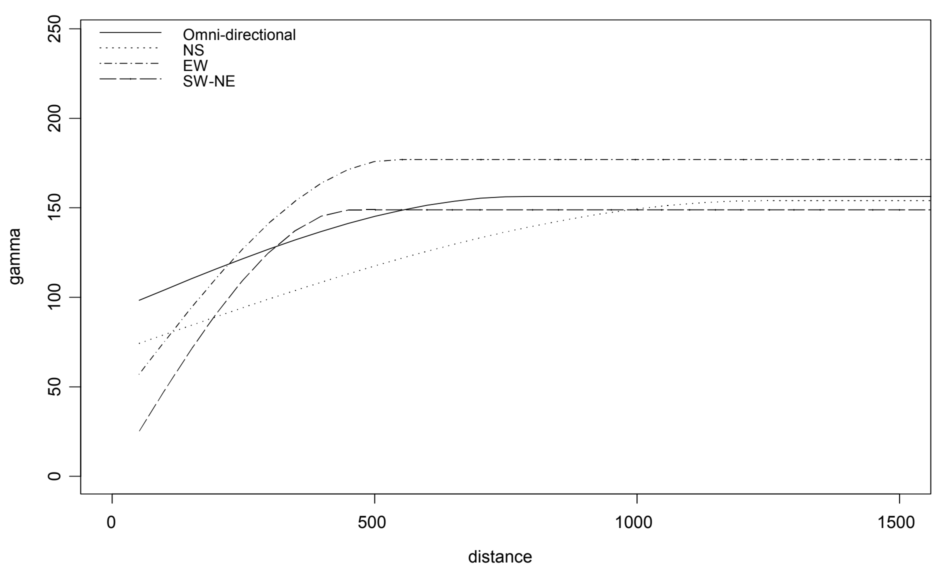


Figure 5b. Theoretical-directional variograms (spherical model) of Semivariance in the Entiat

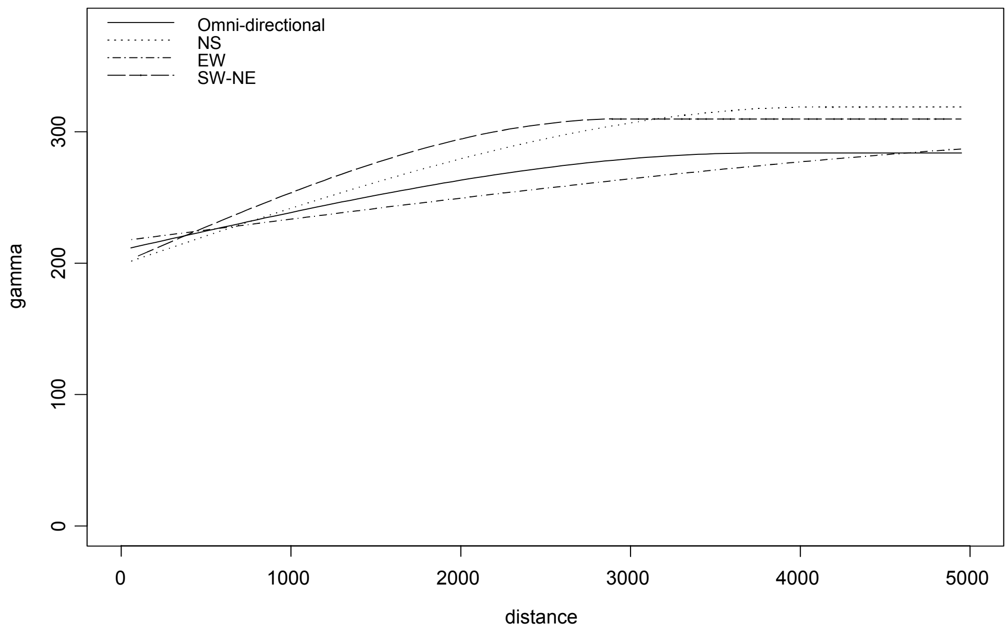


Figure 5c. Theoretical-directional variograms (spherical model) of Semivariance in the Entiat

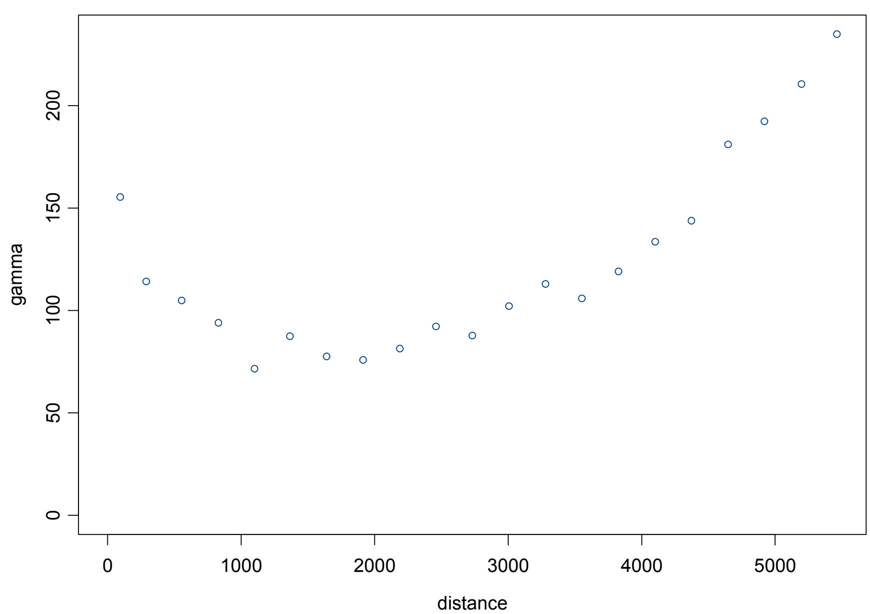
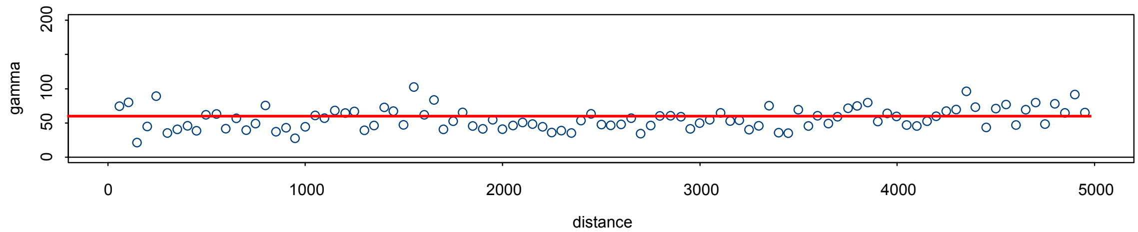


Figure 6 Empirical omni-directional variogram of MFRI (wave/hole model) as a function of distance (m) for the Nile study area.

A)



B)

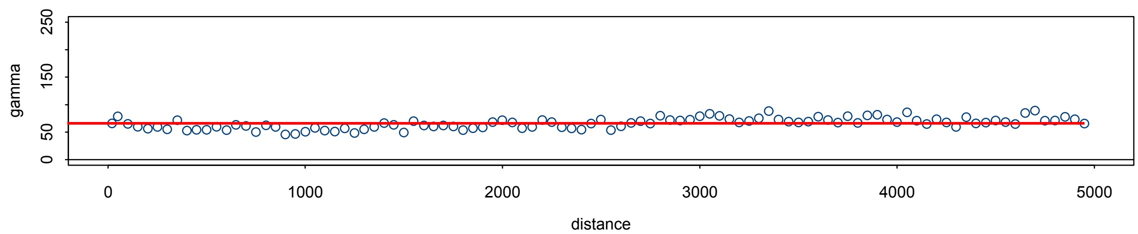


Figure 7 Semivariance measures of gamma (y-axis) for the A) Frosty Creek and B) Quartzite study areas as a function of distance (m) (x-axis). Red line indicates mean sample variance. Empirical variograms show that semivariance at each distance class is approximately equal to the total sample variance.

Topographic and physiographic variables

The spatial structures of three topographic (elevation, slope and aspect) and physiographic (winter solar radiation, summer solar radiation and topographic relative moisture) variables were assessed. Variograms of elevation for all areas except the Swauk were best fit with linear models suggesting a large-scale trend in the distribution but no local pattern within the scale of sampling. In the Swauk, variograms were fit with the spherical model where elevation exhibited spatial dependence to a range of 2.4 km; where spatial dependence explained 38% of the sample variance for elevation. Semivariance decomposed over direction showed elevation was 19% anisotropic with effective ranges being: 5398 m, 4357 m, 2596 m, and 1027 m in the EW, NS, NW-SE, and SW-NE directions.

Similar large-scale trends in slope were discernable from the linear models for the Nile, South Deep, Frosty Creek and Quartzite suggesting a large-scale trend in the distribution but no local pattern within the scale of sampling. The Swauk and Nile study areas both exhibited local trends that were best-fit by a spherical model, where the respective ranges and proportions of spatial dependence were 1.2 km and 885 m and 12% and 53%. Semivariance values for aspect were highly variable at short distances (d<500 m) in the Swauk, Nile, and Entiat, then decreased to a constant γ(h) value, suggesting low variance with increasing distance. The empirical variograms were not fit to models given the highly variably nature. However, the Frosty Creek, Quartzite and South Deep study areas exhibited local trends with aspect that were best-fit by a spherical model, where the respective ranges and proportions of spatial dependence were 1.6 km, 1.1 km, and 840 m and 67%, 83%, and 49%. (For complete overview of model parameters see appendix A)

The heterogeneity of the sites was most easily discernable in the topographic and physiographic variance maps. The spatial structures of fire occurrence and heterogeneity of spatial constraints were apparent when clustered groups were overlaid on the variance maps (Appendix C).

Table 6 Spatial structures of fire occurrence over global scales (entire study area) and local scales (variation within study area). ** indicate p<0.01.

	Global Study Area Scale		Local Scales within Study Area	
Site	Mantel's Correlation	Moran's Relationship	Semivariance Model	Proportion (%) of Spatial Dependence
Nile	.50**	+ < 3km	Wave/Hole	0
Swauk	.54**	+ < 5km	Spherical	54
Entiat	.34**	0	Spherical	41

Frosty Creek	.35**	0	Random	0
Quartzite	.19**	0	Random	0
South Deep	.29**	0	Spherical	26

Discussion

Statistical properties of historical, low-severity fire regimes are scale-dependent (Falk 2004, Moritz 2004, McKenzie and Hessl 2004). Fire occurrence operates at varying spatial scales, reflecting topographic properties of local landscapes. In complex rugged terrain fire occurrence varied over a distance of 800 m or less, whereas in more open and rolling terrain, the spatial scale of fire occurrence was not controlled by landform. Results illustrate that the statistical spatial characteristics of the fire regime change with landform characteristics within a forest type, suggesting that a simple relationship between fire frequency and forest-type does not exist. Quantifying the spatial structures in fire occurrence associated with environmental variation demonstrated that fire regime variability is scale and location dependent.

The theoretical variograms for the topographic and physiographic variables reflected considerable variation in the range of spatial dependence, suggesting different spatial scales of variation in biotic environments at different sites. However, when individual environmental variables were tested for effects on the synchrony of fire occurrence, no significant correlations were found except for elevation in the Nile. Although environmental variability may be intrinsic to low-severity fire regimes, individual environmental variables alone are not good predictors of variability in fire frequency or temporal pattern. Elevation as a correlate of fire synchrony in the Nile may be a function of the smooth elevational gradient captured in the sample area. Typically, relationships between elevation and fire frequency are observed over longer gradients, via the direct effect elevation has on fuel moisture and fuel production (Heyerdahl 2001; Taylor and Skinner 2004). Fire frequency is often negatively correlated with elevation, such that as elevation increases, fuel moistures increase and productivity decreases, decreasing fire frequency. In Nile Creek, the elevation gradient is too short to elicit observable differences in fire frequency. I observed a decreasing synchrony between temporal patterns of fire with changes in elevation, but this likely reflects only the smooth elevational gradient across the sample area within the study area and is not likely a response to changes in fuel moisture or abundance.

Global vs. local spatial dependence: top-down vs. bottom-up control

Results from the Mantel's test, variograms and Moran's I depicted varying scales of spatial structure associated with fire occurrence that could be categorized as having either global (across study area) or local (changing within the study area) spatial dependence (table 6), and vary regionally (among study areas). This categorization provides an initial framework from which inferences on the operative controls (top-down or bottom-up) influencing fire regime variability can be made (Lertzman and Fall 1998).

Strong local spatial dependence with relatively short effective ranges would imply that the variability associated with the fire regime is primarily a function of fine-scale factors (i.e. topography and fuels), collectively imposing constraints on the spatial patterns of fire from the bottom-up (Levin 1992). Weak, local spatial dependence with relatively long effective ranges would imply that the variability associated with the fire regime is influenced by larger scale constraints (i.e. climate/weather), being imposed from the top-down. When global spatial dependence is strong, the primary control is being exerted from the bottom-up. Conversely when global spatial dependence is weak but varies regionally, the controls originate from top-down influences.

The strength of spatial dependence within and among the study areas varied regionally with latitude, being strongest for study areas in the southern portion of the North Cascades and weakening gradually moving north and east through the Okanogan Highlands. Historical fire regimes in the South Deep and Quartzite exhibited weak global and local spatial dependence, suggesting that their spatial variability is primarily a function of climate though portions of the variability may be marginally entrained by topography. Topography in the Okanogan Highlands is gently rolling, with broad U-shaped valleys, and despite being partially in the rain shadow of the Cascades, the climate is wet and cool relative to the other study areas. Fire return intervals were comparatively longer in South Deep and were similar over greater distances that the other study areas, further suggesting that fires in the Okanogan Highlands were perhaps larger and less frequent than fires in the central Cascades (Hessl et al. 2004). Schellhaas et al. (2000a, b) estimated fire sizes ranged from tens of ha to 6000 ha in South Deep and tens of ha to 3000 ha in Quartzite. From the fire size estimations and ground observations made by Schellhaas et al. (2000a, b), it was evident that fire frequently crossed topographic barriers in both South Deep and Quartzite study areas.

In contrast, in the Nile, Swauk, and Entiat, historical fire regimes exhibited moderate to strong global spatial dependence, suggesting that the spatial variability was primarily a function of topography. The landscapes of the Nile, Swauk, and Entiat were produced by mountain glaciations that created complex topography that is broken and deeply incised with steep, v-shaped valleys. The climate in this portion of the Cascades is warmer and drier, fire-return intervals were historically shorter, and fire sizes were smaller (< 300 ha) on average than in the Okanogan Highlands (Schellhaas et al. 2002; Hessl et al. 2004). However, within the Nile, Swauk, and Entiat, the local spatial dependence was variable. Variograms of mean fire return intervals for the Swauk and Entiat exhibit strong, monotonic local spatial dependence that was highly constrained, suggesting that at finer scales, topography is influencing the modal fire size within the study areas. In the Nile, the variograms of mean fire return intervals are quite different. The variogram model indicates that fire return intervals for recorder trees close together were very different and became more similar with increasing distance. The presence of global and local spatial dependence in the Swauk and Entiat suggests that bottom-up controls via aggregate topographic effect, were the primary controls of spatial variability in the historic fire regimes. The presence of strong, global spatial dependence without local spatial dependence in the Nile suggests that topography is an important influence on fire regimes at the study area scale but lacks control at finer scales.

Fire regimes in Frosty Creek exhibited moderate global and no local spatial dependence, indicating that although topography contributes to fire regime variability, it is not the primary control. Topography of the Frosty Creek study area generally lacks distinctive features and is representative of what is seen in the Okanogan Highlands. Topographic barriers in this gentle terrain will not effectively impede fire spread. In Frosty Creek, the largest estimated fire size was 3400 ha in 1812, and average fire size from 150-1910 was 650 ha (Schellhaas et al. 2002).

Guidelines for future research

Fire regimes are complex systems that represent an aggregate of spatial and temporal properties. The spatial and temporal resolution of this dataset allowed for a statistical analysis of the range of spatial scales associated with low-severity fire regimes and for inferences about the predominant controls. Fire history datasets of this scope are rarely collected due to the effort, time, and cost required. Because these datasets are rare, a fundamental question arises: how much data are enough?

Study areas selected to represent the range of conditions within the ponderosa pine ecosystem in eastern Washington showed regional differences in low-severity fire regimes within a 300-km distance. However, despite extensive sampling within sites, intra-site differences were not always detectable. Of the fire history sites that exhibited strong, global spatial dependence (Swauk, Nile, and Entiat), the Nile was the smallest area sampled (3200 ha) compared to the Swauk and Entiat, which are three times as large (11000 and 13000 ha). The inability to detect local spatial dependence in the Nile may be a function of sampling area, the lack of topographic features within the sampling area, or both.

Greater sampling extent may be more important for determining local spatial variability than the number of fire-scarred trees sampled. Local spatial variability was undetectable in the smaller sample areas (Nile, Frosty Creek, and Quartzite, 2300-3200 ha), even with intensive fire-scar sampling (n = 142-420 trees), but was detectable in the larger sample areas (Swauk, Entiat and South Deep, 11000-12747 ha) where similar numbers of fire-scarred trees were sampled (n= 168-665 trees) (table 1). The ability to detect local-scale spatial dependence within the larger study areas (Swauk, Entiat and South Deep) and not in the smaller ones (Frosty Creek, Quartzite and Nile) may imply that the sampling extent may not have been large enough to include topographic features that affect synchrony in fire occurrence (Allen and Hoekstra 1991; Levin 1992; Legendre and Legendre 1998).

If our goal is to infer the controls operating on an ecosystem process, such as fire, we must sample the process at the same scales at which the controls operate (Urban et al. 1987; Allen and Hoekstra 1991; Levin 1992; Dutilleul 1998; Lertzman and Fall 1998). For example, in the Nile, all recorder trees were sampled within one drainage of the watershed, whereas in the Swauk, recorder trees were sampled in all drainages contributing to the watershed (a complete topographic unit). Sample points in the Swauk, Entiat and South Deep straddled topographic features (ridges and valleys) rather than one valley. Intensive sampling at the sub-watershed scale, (e.g., the Nile) may be more appropriate for testing hypotheses regarding fuel constraints on fire occurrence than for topographic constraints (McKenzie et al. 2004).

If prior knowledge exists regarding the spatial distributions of mechanisms being analyzed, it can be used to optimize the sampling strategy (Legendre et al. 2002). Augmenting the sample areas in the Nile, Frosty Creek and Quartzite to include all of the drainages contributing to the watershed would increase the ability to infer the mechanisms influencing the spatial patterns of fire occurrence across the watershed. Similarly, regional scale analysis of how climatic controls influence fire occurrence requires an even broader sampling strategy. Hessl et al. (2004), with the same dataset, found that individual study areas were too small and probably too clustered to capture within-site spatial gradients in climate.

Distance between sampling units may also be an important factor in assessing the spatial variability of fire regimes. The effective ranges in the Swauk, Entiat, and South Deep identified by variogram models were equivalent to areas of 40 ha, 180 ha and 4300 ha respectively. I inferred from this that the modal fire sizes in the topographically complex Swauk and Entiat were fairly small. Wright and Agee (2004) found that in the Teanaway watershed, (immediately adjacent to the west of the Swauk), the median fire size was 989 ha, but the spatial resolution of the sample (1.6 km) between recorder trees was such that the smallest fire size detectable was approximately equal to the modal fire size identified in the Entiat (180 ha). Sampling at a 1-km resolution may miss the short-range, local spatial dependence that was detected in the Swauk. Utilizing the scale dependent information can help determine the resolution of the samples needed to optimize theoretical models of spatial auto-covariance (Legendre et al. 2002). Ultimately, the scope of a study is limited by the extent and arrangement of the observations in time and space (Allen et al. 1984; Hoekstra et al. 1991, Legendre and Legendre 1998).

Implications for management

As the land management paradigm shifts from fire suppression to re-introduction of fire and ecosystem restoration in arid mountain forests of the western North America, how can management prescriptions be applied across landscapes when it is known that historical fire regimes varied in response to different controls at different scales? The current template for these decisions relies on coarse-scale analyses that have identified areas with large departures from the historical range of variability for fire occurrence as the highest priorities for treatment (e.g. fire regime condition class three [FRCC3], Schmidt et al. 2002), but these landscape classifications lack information regarding spatial variability at the finer scales relevant for management. My analysis demonstrates that fire regimes are a scale dependent process that is highly variable within a single ecosystem type. A coarse scale approach to restoration ignores this variability, which suggests that an alternative approach to classifying and prioritizing treatment areas is needed.

One suggested alternative has been to include local classifications of plant association groups (PAG) (Daubenmire 1968) as a context to provide greater utility in identifying and prioritizing areas in need of fire restoration (Brown et al. 2004; Wright and Agee 2004). However, in this study I found that the variability associated with eastern Washington fire regimes varied within a plant association group (e.g. dry Douglas-fir, dry grand fir, etc), probably as much as it does among groups. Similarly, Heyerdahl (2001) found that fire occurrence in eastern Oregon varied simply with location (N-S) more strongly than it did with forest type. Given the spatial and temporal variations associated with these fire regimes, it is important that the geographic, topographic, and sub-ecoregional (Hessburg et al. 2000) context be considered when restoration efforts are being prioritized.

Depending upon restoration goals, fire-regime scale dependencies may influence decisions about where and when to allow wildfires to burn versus using prescribed fire. Individual fire-size reconstructions from the Pacific Northwest (Heyerdahl 2001; Schellhaas 2002a; Wright and Agee 2004) indicate that fires were generally small, independent, but synchronous events. Although large fires did occur in the past, they were typically not comparable in size to the fires that have occurred in the past few decades. In contrast, exceptionally large wildfires burned in the Entiat river drainage in 1970, and again in 1994 (Agee 1993). These complexes of wildfires burned tens of thousands of hectares, whereas the historical modal fire sizes suggested by my analysis were ca.180 ha in the Entiat. Model variograms for current fire regimes in the Entiat would most likely depict longer effective ranges or none at all, indicating that bottom-up controls are no longer in effect. Fire regimes are no longer controlled by the predominant controls of the past.

By identifying the scale dependencies associated with specific fire regimes we can match the fire regime to the inherent scales of the controlling factors (i.e. topography, climate) with greater precision, thereby increasing our abilities to evaluate their co-varying relationship and assess how the current regime is deviating from its historic pattern (Falk 2004). Taylor and Skinner (2004) found that the spatial and temporal variations for fire regimes in the Klamath Mountains before fire suppression were consistent with the tactical approach by land managers to use topographic features as fire boundaries when setting prescribed fires in highly complex terrain. Scaling relations of fire regimes may also be useful for prioritizing restoration efforts. If current fire size exceeds the range of its historical spatial dependence (i.e., beyond the boundaries of topographic units) we may infer that a control is no longer in effect and therefore prioritize these locations for treatments that restore the historic controls, e.g., low-severity fires that reduce fuel connectivity such that topographic units once more function as fire boundaries.

Conclusions

Spatial controls on low-severity fire regimes within similar dry forest ecosystem types operate at varying spatial scales, reflecting topographic properties of local landscapes. However, only portions of the spatial variability in fire events can be attributed to topography. In complex, rugged terrain, the effective ranges in variogram models covered 150 ha or less, whereas in more open and rolling terrain, the spatial scale of fire occurrence was not controlled by landform. Results illustrate that the statistical spatial characteristics of fire regimes change with landform characteristics within a forest type, suggesting that a simple relationship between fire frequency and forest type does not exist. Quantifying the spatial structures in fire occurrence associated with topographic variation demonstrated that fire regime variability is scale and location dependent. By identifying the scale dependencies associated with specific fire regimes we can match the regime to the scales of the controlling factors with greater precision, thus increasing our abilities to evaluate their relationship. Understanding these multi-scale dependencies can, in turn, inform the design and application of fire management, including hazardous fuel treatments and the use of fire for ecosystem restoration.

References

Agee, J. K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington D.C.

Agee, J.K. 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management 127: 55-66.

Allen, T.F.H. and Starr, T.B. 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press, Chicago, Illinois, USA.

Allen, T.F.H. and Hoekstra, T.W. 1991. Role of heterogeneity in scaling of ecological systems under analysis. In: Kolasa, J. and Pickett, S.T.A. (eds), Ecological Heterogeneity. Ecological Studies 86. Springer-Verlag, New York, New York, USA, pp. 47-68.

Alt, D.D. and Hyndman, D.W. 1984. Roadside Geology of Washington. Mountain Press, Missoula, Montana, USA.

Baker, W.L. 1989. Effect of scale and spatial heterogeneity on fire-interval distributions. Canadian Journal of Forest Research 19:700-706.

Baker, W.L. 1993. Spatially heterogeneous multi-scale response of landscapes to fire suppression. OIKOS 66:66-71.

Baker, W. L. and Ehle, D. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31:1205-1226

Beatty, R.M. and Taylor, A.H. 2001. Spatial and temporal variation in fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. Journal of Biogeography 28:955-966.

Bekker, M.F. and Taylor, A.H. 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade Range, thousand Lakes Wilderness, California, USA. Plant Ecology 155:15-28.

Brown, R.T., Agee, J.K. and Franklin, J.F. 2004. Forest restoration and fire: principles in the context of place. Conservation Biology 18:903-912.

Burgess, T.M. and Webster, R. 1980a. Optimal interpolation and isarithmic mapping of soil properties I. The semi-variogram and punctual Kriging. Journal of Soil Science 31: 315-331.

Burgess, T.M. and Webster, R. 1980b. Optimal interpolation and isarithmic mapping of soil properties II. Block Kriging. Journal of Soil Science 31: 333-341.

Camp, A., Oliver, C., Hessburg, P. and Everett, R.L. 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. Forest Ecology and Management 95: 63-77.

Clark, K.R. 1993. Non-parametric multivariate analyses of changes in community structure. Australian Journal of Ecology 18:117-143.

Cliff, A. D. and Ord, J. K. 1981. Spatial processes: Models and Applications. Pion Ltd., London.

Cressie, N. 1991. Statistics for Spatial Data. J. Wiley. New York, New York, USA.

Cressie, N. 1985. Fitting variogram models by weighted least squares. Mathematical Geology. 17: 563:568.

Daly, C., Neilson, R.P. and Phillips, D.L. 1994. A digital topographic model for distributing precipitation over mountainous terrain. Journal of Applied Meteorology 33:140-158.

Daubenmire, R. F. and Daubenmire, J. B. 1968. Forest vegetation of eastern Washington and northern Idaho: Washington Agricultural Experiment Station, Technical Bulletin. Pullman, WA, USA.

Dutilleul, P. 1998. From forest stands to landscapes: Spatial scales and the roles of disturbances. In: Peterson D.L. and Parker V.T. (eds), Ecological Scale. Columbia University Press, New York, New York, USA, pp. 369-386.

Dorner, B., Lertzman, K. and Fall, J. 2002. Landscape pattern in topographically complex landscapes: issues and techniques for analysis. Landscape Ecology 17: 729-743.

ESRI. 2004. ArcGis. Version 8.1 Environmental Systems Research Institute, Inc., Redlands, CA.

Everett, R.L., Schelhaas, R., Keenum, D., Spubeck, D. and Ohlson, P. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129: 207-225.

Falk, D.A., 2004. Scale dependence of probability models for fire intervals in a ponderosa pine ecosystem. Dissertation. University of Arizona, Tucson, Arizona, USA.

Fortin, M.-J. and Gurevitch, J., 1993. Mantel tests: spatial structure in field experiments. In: Scheiner, S.M. and Gurevitch, J. (eds), Design and Analysis of Ecological Experiments. Chapman and Hall, New York, New York, USA, pp. 342-359.

Franklin, J.F. and Dyrness, C.T., 1988. Natural vegetation of Oregon and Washington. Oregon State University Press, Eugene, Oregon, USA.

Gardner, R.H. and O'Neill, R.V. 1991. Pattern, process and predictability: the use of neutral models for landscape analysis. In: Turner, M.G. and Gardner, R.H. (eds), Quantitative Methods in Landscape Ecology. Springer-Verlag, New York, New York, USA, pp. 289-307.

Gedalof, Z. M., Peterson, D. L. and Mantua, N. J. 2004. Atmospheric, climatic and ecological controls on extreme wildfire years in the northwestern United States. Ecological Applications (in press).

Goovaerts, P. 1997. Geostatistics for Natural Resources Evaluation. Oxford University Press, New York, New York, USA.

Harrod, R. J., McRae, B. H. and Hartl, W. E. 1999. Historical stand reconstruction in ponderosa pine forests to guide silvicultural prescriptions. Forest and Ecology Management 114:433-446.

Hemstrom, M.A. and Franklin, J.F. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quaternary Research 18:32-51.

Hessl, A.E., McKenzie, D. and Schellhaas, R. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14: 425-442.

Heyerdahl, E. K., Brubaker, L. B. and Agee, J. K., 2001. Spatial controls of historical fire regimes: a multiscale example from the interior West, USA. Ecology 82(3): 660-678.

S-PLUS. Version 6.0. 2000. Insightful, Seattle, WA, USA.

Hessburg, P.F., Salter, R.B., Richmond, M.B., and Smith, B.G. 2000. Ecological subregions of the Interior Columbia Basin, USA. Applied Vegetation Science 3: 163-180.

Isaaks, E. H. and Srivastava, R. M. 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, New York, USA.

Johnson, E.A. and Gutsell, S.L. 1994. Fire frequency models, methods, and interpretations. Advances in Ecological Research 25: 239-287.

Johnson, E. A. and Larsen, C. P. S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. Ecology 72: 194-201.

Kumar, L., Skidmore, A., and Knowles, E. 1997. Modeling topographic variation in solar radiation in a GIS environment. International Journal of Geographic Information Science 1(5): 475-497.

Legendre, P. 2000. Comparison of permutation methods for the partial correlation and partial Mantel tests. Journal of Statistical Computation and Simulation 67: 37-73.

Legendre, P. and Fortin, M.-J. 1989. Spatial pattern and ecological analysis. Vegetation 80:107-138.

Legendre, P., and Legendre, L. 1998. Numerical Ecology, Second English Edition. Elsevier Science B.V., Amsterdam, Netherlands.

Legendre, P. and Troussellier, M. 1988. Aquatic heterotrophic bacteria: modeling in the presence of spatial autocorrelation. Limnology and Oceanography 33: 1055-1067.

Lertzman, K., and Fall, J. 1998. From forest stands to landscapes: Spatial scales and the roles of disturbances. In: Peterson, D.L. and Parker, V.T. (eds), Ecological Scale. Columbia University Press, New York, New York, USA, pp 339-367.

Levin, S.A. 1992. The problem of pattern and scale in ecology. Ecology 73:1943-1967

Lillybridge, T. R., Kovalchik, B. L., Williams, C. K. and Smith, B. G., 1995: Field Guide for Forested Plant Associations of the Wenatchee National Forest. United States Department of Agriculture, Forest Service, General Technical Report, Pacific Northwest Research Station, PNW-GTR-359, Portland, OR, USA.

Mantel, N. 1967. The detection of disease clustering and a generalized regression approach. Cancer Research 27: 209-220.

Matheron, G. 1965. Regional Variables and Their Estimation. Masson, Paris, France.

McKenzie, D., Gedalof, Z., Peterson, D. L. and Mote, P. 2004a. Climatic change, wildfire, and conservation. Conservation Biology 18:890-902.

McKenzie, D., Hessl, A.E., Kellogg, L-K.B., and Morgan-Martinez, A. 2004b. Using neutral models to identify constraints on low-severity fire regimes. In review.

McKenzie, D., Peterson, D.L. and Alvarado, E. 1996. Extrapolation problems in modeling fire effects at large spatial scales: a review. International Journal of Wildland Fire 6:165-176.

Miller, C. and Urban, D. 1999. Forest pattern, fire, and climatic change in the Sierra Nevada. Ecosystems 2:76-87.

Oden, N. L. 1984. Assessing the significance of spatial correlograms. Geographic Analysis 16: 1-16.

Oden, N.L. and Sokal, R.R. 1992. An investigation of three-matrix permutation tests. Journal of Classification 9: 275-290.

Parker, A.J. 1982. The topographic relative moisture index: an approach to soil moisture assessment in mountain terrain. Physical Geography 3:160-168.

Peterson, D. L. and Parker, T.V. (eds) Dimensions of scale in ecology, resource management, and society. In: Ecological Scale Theory and Applications. Columbia University Press, New York, New York, USA. pp. 499-522.

Pickett, S.T.A., Kolasa, J., Armets, J.J. and Collins, S.L. 1989. The ecological concept of disturbance and its expression at various hierarchical levels. OIKOS 54:129-136.

Romme, W.H. and Knight, D.H. 1981. Fire frequency in subalpine forest succession along a topographic gradient in Wyoming. Ecology 62: 319-326.

Romme, W.H. and Knight, D.H. 1982. Landscape diversity: the concept applied to Yellowstone National Park. Ecological Monographs 52:199-221.

Rossi, R.E., Mulla, D.J., Journel, A.G. and Franz, E.H. 1992. Geostatistical tools for modeling and interpreting spatial dependence. Ecological Monographs 62:277-314.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. United States Department of Agriculture, Forest Service, Intermountain Research Station, General Technical Report, INT-115. Missoula, Montana, USA.

Rothermel, R.C. 1983. How to predict the spread and intensity of wildfires. United States Department of Agriculture, Forest Service, General Technical Report, Intermountain Research Station, INT-GTR-143. Missoula, Montana, USA.

Schellhaas, R., Spurbeck, D., Olson, P., Camp, A.E. and Keenum, D. 2000a. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, Report to the Colville National Forest on the Results of the South Deep Watershed Fire History Research. Wenatchee, Washington, USA.

Schellhaas, R., Spurbeck, D., Olson, P., Camp, A.E. and Keenum, D. 2000b. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, Report to the Colville National Forest on the Results of the Quartzite Watershed Fire History Research. Wenatchee, Washington, USA.

Schellhaas, R., Spurbeck, D., Olson, P., Keenum, D. and Conway, A. 2002. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, Report to the Okanogan-Wenatchee National Forest on the Results of the Frost Creek Planning Area Fire History Research. Wenatchee, Washington, USA.

Schoennagel, T.L., Veblen, T.T. and Romme, W.H. 2004. The interaction of fire, fuels and climate across Rocky Mountain forests. BioScience 54: 661-676.

Schmidt, K. M., Menakis, J. P., Hardy, C. C., Hann, W. J. and Bunnell, D. L. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-87. Fort Collins, Colorado, USA.

Smouse, P. E., Long, J. C. and Sokal, R. R. 1986. Multiple regression and correlation extensions of the Mantel test of matrix correspondence. Systematic Zoology 35: 627-632.

Sokal, R.R. and Rolf, F. 1995. Biometry: The Principles and Practices of Statistics in Biology Research. W.H. Freeman, New York, New York, USA.

Stephenson, N.L. 1990. Climatic controls on vegetation distribution: the role of the water balance. American Naturalist 135:649-670.

Swanson, F.J., Kranz, T.K. and Caine, N., and Woodmansee, R.G. 1988. Landform effects on ecosystem patterns and processes. Bioscience 38(2): 92-98.

Swetnam, T. W. 1993. Fire history and climate change in Giant Sequoia groves. Science 262:885-889.

Swetnam, T.W., and Baisan, C.H. 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. In: Allen, C. D. (eds), Fire Effects in Southwestern Forests, Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, March 29-31, 1994. General Technical Report RM-GTR-286: 11-32, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Swetnam, T. W., Allen, C. D. and Betancourt, J. L. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9:1189-1206.

Tande, G. F. 1979. Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. Canadian Journal of Botany 57: 1912-1931.

Taylor, A. H. and Skinner, C. N. 2003. Spatial and temporal patterns of historic fire regimes and forest structure as a reference for restoration of fire in the Klamath Mountains. Ecological Applications 13:704-719.

Taylor, A.H. and Skinner, C.N. 1998. Fire History and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management 44:1-17.

Turner, M.G. 1989. Landscape Ecology: The effect of pattern on process. Annual Review of Ecology and Systematics 20: 171-197.

Turner, M.G. and Dale, V.H. 1991. Modeling landscape disturbance. In: Turner, M.G. and Gardner, R.H. (eds), Quantitative Methods in Landscape Ecology. Springer-Verlag, New York, New York, USA, pp. 324 –352.

Turner, M.G., Gardner, R.H. and O'Neill, R.V. 2001. Landscape Ecology in Theory and Practice, Pattern and Process. Springer-Verlag, New York, New York, USA.

Urban, D.L., O'Neill, R.V. and Shugart, H.H. 1987. Landscape ecology. BioScience 37:119-127.

Urban, D.L., Goslee, S., Pierce, K. and Lookingbill, T. 2002. Extending community ecology to landscapes. Ecoscience 9(2): 200-202.

Veblen, T.T., Kitzberger,T. and Donnegan. J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecological Applications 10:1178-1195.

Wagner, H. H. 2003. Spatial covariance in plant communities: integrating ordination, geostatistics, and variance testing. Ecology 84: 1045-1057

Webster, R. and Oliver, M.A. 2001. Geostatistics for environmental scientists. John Wiley and Sons, New York, New York, USA.

White, P.S. and Pickett, S.T.A. 1985. Natural disturbance and patch dynamics: an introduction. In: White, P.S., and Pickett, S.T.A. (eds), The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, New York, New York, USA. pp. 3-13.

Williams, C. K. and Lillybridge, T.R. 1983. Forested plant associations of the Okanogan National Forest. Research Publication R6-Ecol-132b. Portland, OR:

United States Department of Agriculture, Forest Service, Pacific Northwest Region. Wenatchee, Washington, USA.

Williams, C. K., Kelley, B. F., Smith, B. G. and Lillybridge, T.R. 1995. Forested Plant Associations of the Colville National Forest. General Technical Report PNW-GTR-360. Portland,OR. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Wright, C.S. and Agee, J.K. 2004. Fire and vegetation history in the eastern Cascade Mountains, Washington. Ecological Applications 14(2): 443-459.

Appendix A. Parameters from theoretical models of semivariance.

Table A1. Parameters from theoretical models of semivariance for MFRI and topographic/physiographic variables in the Nile. Grey shading indicates parameters were not detectable or not significantly different from zero.

OMNI-DIRECTIONAL		DIRECTIONAL				
NILE		**NILE**				
Hole Model						
MFRI		**MFRI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1000.00	RANGE	1821.00			
SILL	-1.92	SILL	-78.00			
NUGGET	107.68	NUGGET	142.00			
ELEVATION		**ELEVATION**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	4235.94	6959.15	5553.58	
SILL		SILL	27029.60	16920.20	20397.00	
NUGGET		NUGGET	0.00	0.00	0.00	
SLOPE		**SLOPE**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	885.75	RANGE	337.97	908.33		1254.70
SILL	25.72	SILL	49.53	34.84		21.63
NUGGET	22.70	NUGGET	0.00	14.29		25.86
ASPECT		**ASPECT**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	1048.57			946.30
SILL		SILL	3554.23			3492.40
NUGGET		NUGGET	4509.46			3543.69
FLUX.W		**FLUX.W**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1.10E+03	RANGE	5.39E+02	1.57E+03	1.95E+03	1.32E+03
SILL	2.13E+10	SILL	2.86E+11	8.50E+10	1.94E+11	1.78E+11
NUGGET	9.64E+10	NUGGET	1.61E+10	1.91E+11	1.53E+11	1.23E+11
FLUX.S	1.02E+03	**FLUX.S**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	3.99E+10	RANGE	3.15E+02	1.33E+03	1.91E+03	1.88E+03
SILL	2.54E+10	SILL	6.46E+10	1.81E+10	3.45E+10	2.62E+10
NUGGET		NUGGET	0	4.10E+10	3.61E+10	3.80E+10
TRMI		**TRMI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	272.80	RANGE	362.33	368.73		
SILL	95.60	SILL	102.96	-48.19		
NUGGET	0.00	NUGGET	0.00	141.45		

Table A2. Parameters from theoretical models of semivariance for MFRI and topographic/physiographic variables in the Swauk. Grey shading indicates parameters were not detectable or not significantly different from zero.

OMNI-DIRECTIONAL		DIRECTIONAL				
SWAUK		**SWAUK**				
MFRI		**MFRI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	365.63	RANGE	316.00	366.00	634.00	171.00
SILL	50.92	SILL	25.00	51.00	56.00	87.00
NUGGET	42.32	NUGGET	60.00	42.00	45.00	2.00
ELEVATION		**ELEVATION**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	2397.75	RANGE	5398.23	4357.50	1026.76	2596.18
SILL	7655.62	SILL	5072.85	11074.00	10519.70	8244.14
NUGGET	12132.40	NUGGET	14945.00	11565.60	8427.69	12179.00
SLOPE		**SLOPE**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1222.44	RANGE	459.14	393.58	1070.17	1517.25
SILL	6.50	SILL	19.76	-5.01	14.70	6.94
NUGGET	48.80	NUGGET	34.54	60.08	41.45	48.67
ASPECT		**ASPECT**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	1145.66	3477.20	374.23	435.86
SILL		SILL	-2239.05	-739.94	1392.51	1256.62
NUGGET		NUGGET	9034.62	7364.08	5528.09	5702.76
FLUX.W		**FLUX.W**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1.21E+02	RANGE			1.29E+03	2.64E+02
SILL	2.10E+11	SILL			9.67E+10	8.89E+10
NUGGET	1.14E+11	NUGGET			2.40E+11	2.25E+11
FLUX.S		**FLUX.S**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	4.54E+02	RANGE	3.07E+03	4.10E+03	6.90E+02	2.66E+02
SILL	1.55E+08	SILL	-1.29E+08	-1.36E+08	5.11E+08	3.73E+08
NUGGET	1.04E+09	NUGGET	1.32E+09	1.28E+09	6.91E+08	8.02E+08
TRMI		**TRMI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	1474.65	1435.79	4667.54	744.69
SILL		SILL	15.79	13.33	10.43	-11.50
NUGGET		NUGGET	64.17	70.12	77.90	90.61

Table A3. Parameters from theoretical models of semivariance for MFRI and topographic/physiographic variables in the Entiat. Grey shading indicates parameters were not detectable or not significantly different from zero.

OMNI-DIRECTIONAL		DIRECTIONAL				
ENTIAT						
MFRI		**MFRI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	784.33	RANGE	540.00	1245.00	458.00	
SILL	64.41	SILL	140.00	85.00	149.00	
NUGGET	91.96	NUGGET	37.00	69.00	0.00	
ELEVATION		**ELEVATION**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	4268.25	4292.47		2824.41
SILL		SILL	15474.50	8706.64		10120.50
NUGGET		NUGGET	0.00	929.54		0.00
SLOPE		**SLOPE**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	358.18	184.23	938.92	1161.90
SILL		SILL	53.51	53.05	30.58	28.46
NUGGET		NUGGET	0.00	0.00	22.79	28.36
ASPECT		**ASPECT**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	362.35	RANGE		417.79	2924.43	878.48
SILL	-138.70	SILL		1298.61	1248.96	3570.72
NUGGET	287.60	NUGGET		6495.33	6782.90	4667.29
FLUX.W		**FLUX.W**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	9.37E+02	RANGE	7.85E+02	9.04E+02	3.27E+02	1.12E+03
SILL	5.78E+10	SILL	8.02E+10	6.39E+10	6.21E+10	6.98E+10
NUGGET	2.76E+10	NUGGET	1.20E+10	1.56E+10	1.71E+10	2.22E+10
FLUX.S		**FLUX.S**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	9.76E+02	RANGE	6.99E+02	1414.61	1092.96	8.82E+02
SILL	7.72E+08	SILL	1.04E+09	7.27E+08	5.38E+08	8.06E+08
NUGGET	0.00E+00	NUGGET	-1.70E+08	0.00E+00	1.15E+08	0.00E+00
TRMI		**TRMI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	59.40	RANGE	2380.26	145.74		814.03
SILL	59.10	SILL	12.55	65.65		30.38
NUGGET	9.05	NUGGET	54.32	0.00		37.09

Table A4. Parameters from theoretical models of semivariance for MFRI and topographic/physiographic variables in Frosty Creek. Grey shading indicates parameters were not detectable or not significantly different from zero.

OMNI-DIRECTIONAL		**DIRECTIONAL**				
FROSTY CREEK		**FROSTY CREEK**				
MFRI		**MFRI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE				
SILL		SILL				
NUGGET		NUGGET				
ELEVATION		**ELEVATION**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	5865.20	1331.37	3279.37	4626.54
SILL		SILL	10137.30	7052.78	10420.70	6653.99
NUGGET		NUGGET	0.00	0.00	688.38	1417.50
SLOPE		**SLOPE**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	3061.67	1196.45	2138.13	1037.43
SILL		SILL	24.97	35.26	53.27	20.15
NUGGET		NUGGET	26.99	21.62	20.56	28.28
ASPECT		**ASPECT**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1606.50	RANGE	947.35	1179.61	1732.42	3896.06
SILL	3306.08	SILL	2469.01	4493.34	4084.81	3766.38
NUGGET	1650.35	NUGGET	1502.46	662.96	1489.69	2192.11
FLUX.W		**FLUX.W**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	7.86E+02	RANGE	3.09E+02	1.47E+03	3.07E+03	7.74E+02
SILL	1.05E+11	SILL	1.14E+11	1.09E+11	1.14E+11	6.36E+10
NUGGET	2.46E+10	NUGGET	0.00E+00	3.56E+10	6.85E+10	4.96E+10
FLUX.S		**FLUX.S**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	4.67E+02	RANGE	2.45E+02	1.79E+03	3.28E+02	7.48E+02
SILL	2.64E+10	SILL	2.96E+10	2.15E+10	3.08E+10	1.28E+10
NUGGET	1.76E+09	NUGGET	-5.36E+09	1.08E+10	0.00E+00	1.25E+10
TRMI		**TRMI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	1210.99	294.41	955.79	164.26
SILL		SILL	22.52	58.08	24.23	65.10
NUGGET		NUGGET	69.11	22.81	59.35	11.13

Table A5. Parameters from theoretical models of semivariance for MFRI and topographic/physiographic variables in Quartzite. Grey shading indicates parameters were not detectable or not significantly different from zero.

OMNI-DIRECTIONAL		**DIRECTIONAL**				
QUARTZITE		**QUARTZITE**				
MFRI		**MFRI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	2779.83	RANGE	851.00	172.00		1189.00
SILL	-6.60	SILL	50.00	-141.00		24.00
NUGGET	56.91	NUGGET	13.00	202.00		30.00
ELEVATION		**ELEVATION**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	3614.75	2164.22	4032.88	
SILL		SILL	34932.90	18133.00	48317.90	
NUGGET		NUGGET	0.00	0.00	-4942.58	
SLOPE		**SLOPE**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	283.32	RANGE	435.30	3768.80	4175.92	1893.43
SILL	26.63	SILL	62.86	27.29	41.11	25.70
NUGGET	29.61	NUGGET	0.51	33.86	24.62	20.67
ASPECT		**ASPECT**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	839.04	RANGE	816.20	552.54		
SILL	2386.74	SILL	4634.15	4532.67		
NUGGET	2419.88	NUGGET	0.00	0.00		
FLUX.W		**FLUX.W**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	9.26E+03	RANGE	1.10E+03	2.22E+03	6.93E+02	3.35E+02
SILL	2.26E+11	SILL	2.37E+11	3.19E+11	1.98E+11	2.46E+11
NUGGET	2.07E+11	NUGGET	1.17E+11	8.22E+10	5.10E+10	0.00E+00
FLUX.S		**FLUX.S**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	4.06E+02	RANGE	1.06E+03	2.16E+03	8.40E+02	1.46E+03
SILL	1.70E+101	SILL	7.89E+10	9.66E+10	9.86E+10	4.08E+10
NUGGET	3.81E+09	NUGGET	3.47E+10	1.20E+10	0.00E+00	3.05E+10
TRMI		**TRMI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	1591.40	904.30		557.83
SILL		SILL	43.95	0.52		21.42
NUGGET		NUGGET	40.35	68.24		39.96

Table A6. Parameters from theoretical models of semivariance for MFRI and topographic/physiographic variables in Quartzite. Grey shading indicates parameters were not detectable or not significantly different from zero.

OMNI-DIRECTIONAL		**DIRECTIONAL**				
SOUTH DEEP		**SOUTH DEEP**				
MFRI		**MFRI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	3788.74	RANGE	7260.49	4129.46	2958.81	
SILL	74.55	SILL	81.85	120.85	110.14	
NUGGET	210.67	NUGGET	217.92	199.66	200.32	
ELEVATION		**ELEVATION**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	1187.17	3264.69	1157.22	
SILL		SILL	9392.05	13946.80	7437.88	
NUGGET		NUGGET	0.00	0.00	0.00	
SLOPE		**SLOPE**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	3384.29	791.65	7590.52	3838.99
SILL		SILL	23.84	40.88	42.77	33.45
NUGGET		NUGGET	33.38	15.65	38.63	18.27
ASPECT		**ASPECT**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1172.22	RANGE	1239.05	636.14	1328.58	3719.37
SILL	5596.05	SILL	5177.49	6292.32	6898.06	5322.18
NUGGET	779.49	NUGGET	1209.20	0.00	0.00	2168.31
FLUX.W		**FLUX.W**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	9.61E+02	RANGE	6.08E+02	2.24E+03	1.29E+03	1.00E+03
SILL	1.90E+10	SILL	2.55E+11	5.92E+11	5.14E+11	2.32E+11
NUGGET	9.60E+10	NUGGET	4.38E+10	2.62E+10	0.00E+00	2.35E+10
FLUX.S		**FLUX.S**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE	1.01E+02	RANGE	6.40E+02	2.34E+03		1.08E+03
SILL	1.87E+10	SILL	6.29E+10	1.54E+11		5.40E+10
NUGGET	0.00E+00	NUGGET	0.00E+00	0.00E+00		3.71E+09
TRMI		**TRMI**	**EW**	**NS**	**SWNE**	**NWSE**
RANGE		RANGE	582.95	1048.07	14762.70	2339.39
SILL		SILL	40.07	29.07	-50.71	55.82
NUGGET		NUGGET	56.39	52.44	102.47	38.30

Appendix B. Results from Mantel's and partial Mantel's tests

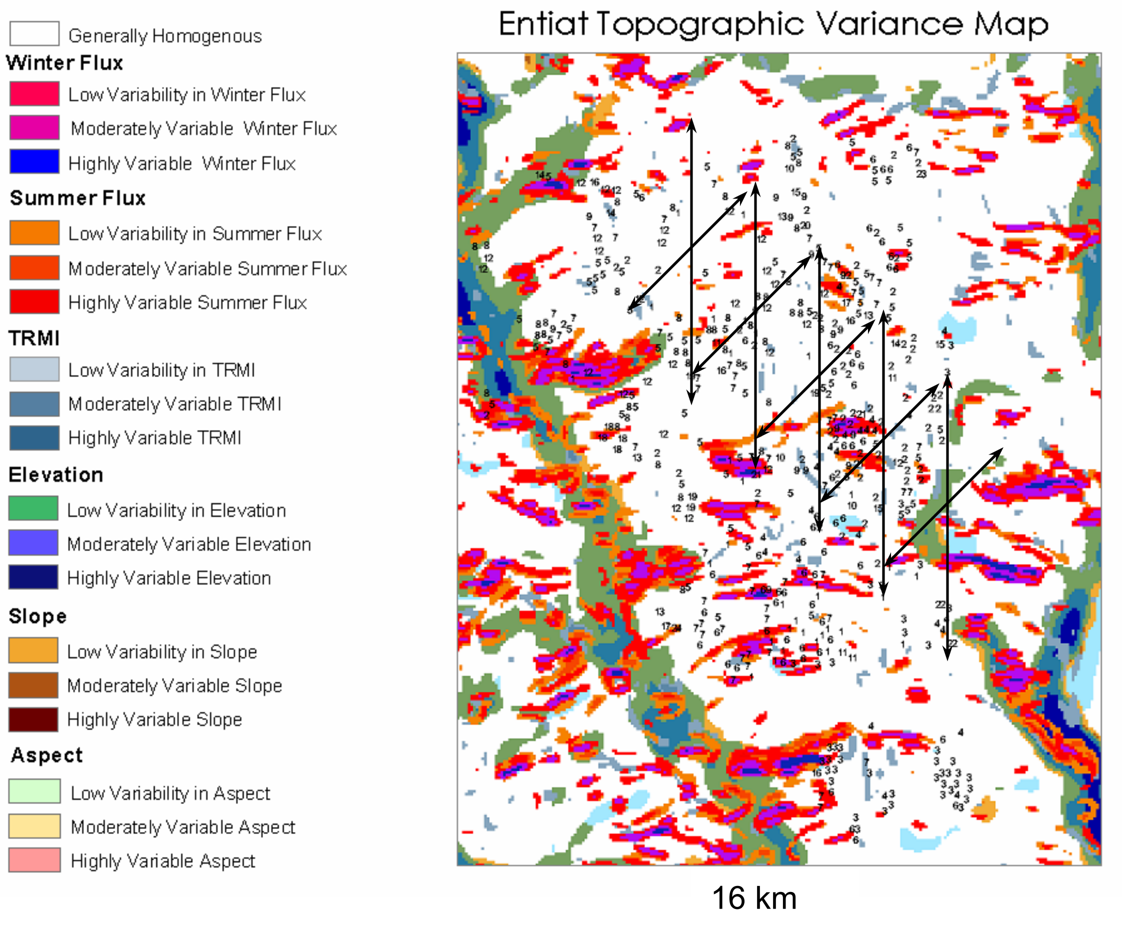
Table B1. Results

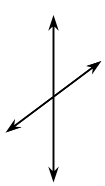
Site and Test	Response (Y)	Predictor (X1)	Predictor (X2)	r	p	Confidence Interval llim (2.5%)	ulim(97.5%)
Nile							
Mantel's	Fire Occurrence	Distance		0.500	0.001	0.482	0.517
Partial Mantel's	Fire Occurrence	Distance+	Elevation	0.439	0.001	0.424	0.456
			Slope	0.500	0.001	0.483	0.519
			Aspect	0.499	0.001	0.482	0.515
			Winter Flux	0.501	0.001	0.483	0.519
			Summer Flux	0.501	0.001	0.485	0.517
			TRMI	0.500	0.001	0.482	0.517
Swauk				**r**	**p**	**llim (2.5%)**	**ulim(97.5%)**
Mantel's	Fire Occurrence	Distance		0.540	0.001	0.534	0.548
Partial Mantel's	Fire Occurrence	Distance+	Elevation	0.540	0.001	0.532	0.548
			Slope	0.540	0.001	0.533	0.548
			Aspect	0.540	0.001	0.533	0.548
			Winter Flux	0.540	0.001	0.533	0.547
			Summer Flux	0.540	0.001	0.533	0.547
			TRMI	0.541	0.001	0.533	0.549
Entiat				**r**	**p**	**llim (2.5%)**	**ulim(97.5%)**
Mantel's	Fire Occurrence	Distance		0.342	0.001	0.330	0.355
Partial Mantel's	Fire Occurrence	Distance+	Elevation	0.336	0.001	0.324	0.349
			Slope	0.343	0.001	0.330	0.356
			Aspect	0.341	0.001	0.330	0.356
			Winter Flux	0.340	0.001	0.328	0.354
			Summer Flux	0.340	0.001	0.328	0.354
			TRMI	0.340	0.001	0.328	0.354
Frosty Creek				**r**	**p**	**llim (2.5%)**	**ulim(97.5%)**
Mantel's	Fire Occurrence	Distance		0.346	0.001	0.332	0.363
Partial Mantel's	Fire Occurrence	Distance+	Elevation	0.346	0.001	0.331	0.363
			Slope	0.346	0.001	0.333	0.362
			Aspect	0.345	0.001	0.331	0.362
			Winter Flux	0.346	0.001	0.331	0.363
			Summer Flux	0.346	0.001	0.331	0.363
			TRMI	0.346	0.001	0.332	0.362

Table B1. (Continued)

Site and Test	**Response**	**Predictor**	**Predictor**			**Confidence Interval**	
Quartzite				**r**	**p**	**llim (2.5%)**	**ulim(97.5%)**
Mantel's	Fire Occurrence	Distance		0.295	0.001	0.270	0.324
Partial Mantel's	Fire Occurrence	Distance+	Elevation	0.292	0.001	0.271	0.319
			Slope	0.295	0.001	0.270	0.326
			Aspect	0.295	0.001	0.272	0.324
			Winter Flux	0.295	0.001	0.270	0.320
			Summer Flux	0.295	0.001	0.268	0.322
			TRMI	0.295	0.001	0.272	0.326
South Deep				**r**	**p**	**llim (2.5%)**	**ulim(97.5%)**
Mantel's	Fire Occurrence	Distance		0.195	0.001	0.178	0.219
Partial Mantel's	Fire Occurrence	Distance+	Elevation	0.196	0.001	0.179	0.220
			Slope	0.203	0.001	0.186	0.222
			Aspect	0.196	0.001	0.176	0.220
			Winter Flux	0.195	0.001	0.177	0.217
			Summer Flux	0.195	0.001	0.174	0.218
			TRMI	0.194	0.001	0.177	0.219

Appendix C. Variance Maps





Range of major axis (1245m) in the NS direction and range of minor axis (458m) in the SWNE direction.

Figure C1. Map of topographic and physiographic variability for the Entiat with semivariogram model measurements of anisotropy for MFRI imposed on landscape.

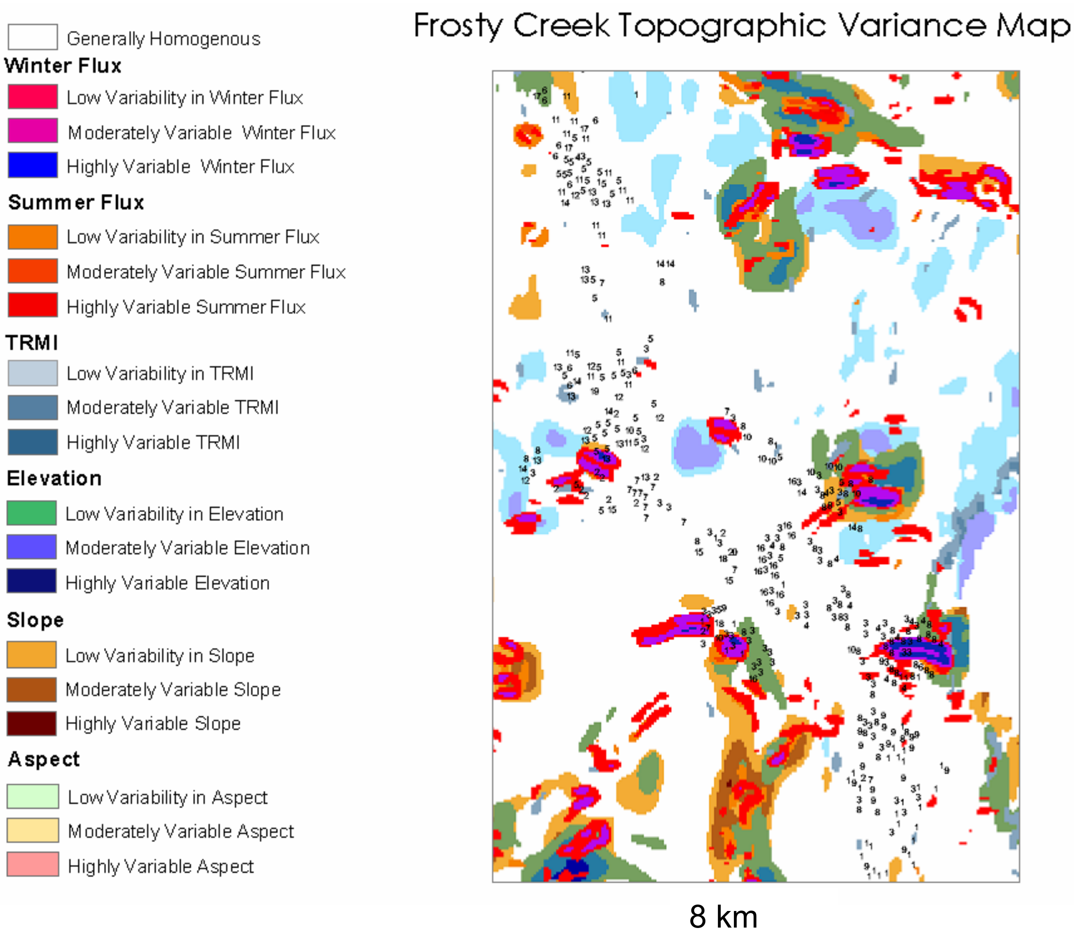


Figure C2. Map of topographic and physiographic variability for Frosty Creek.

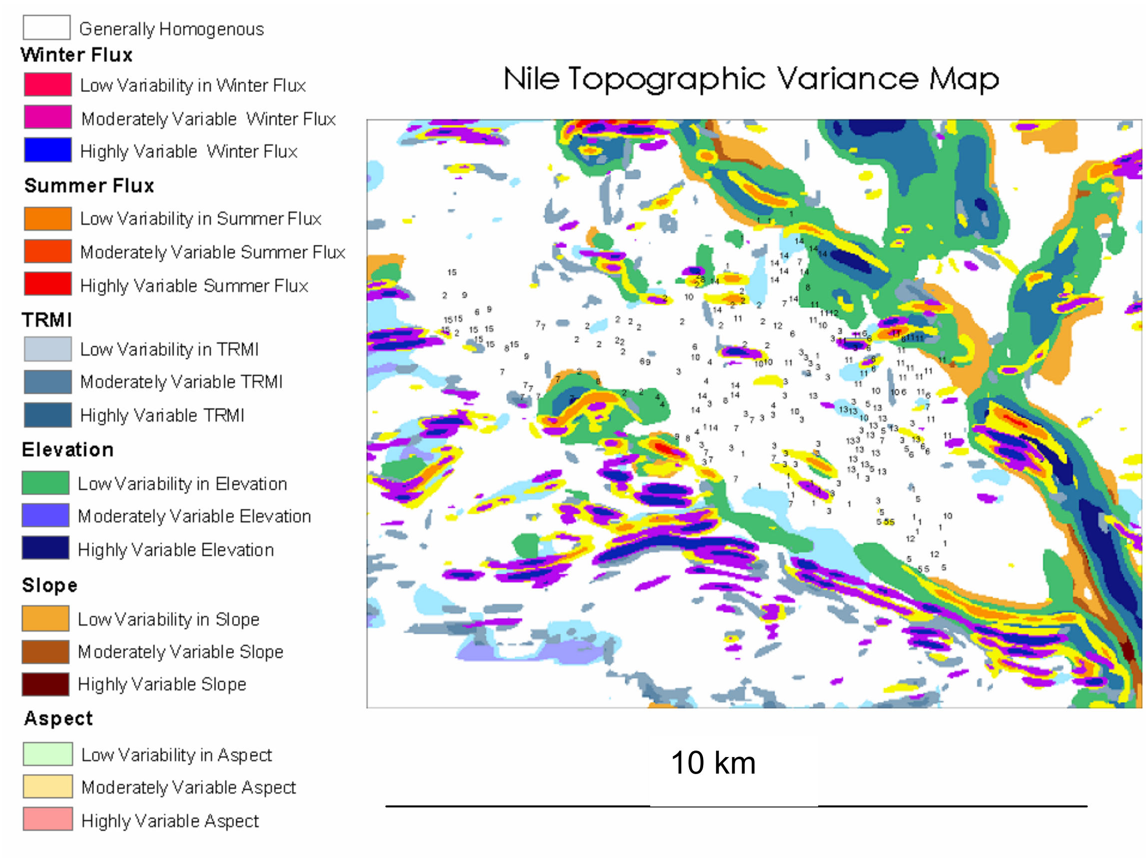


Figure C3. Map of topographic and physiographic variability for the Nile.

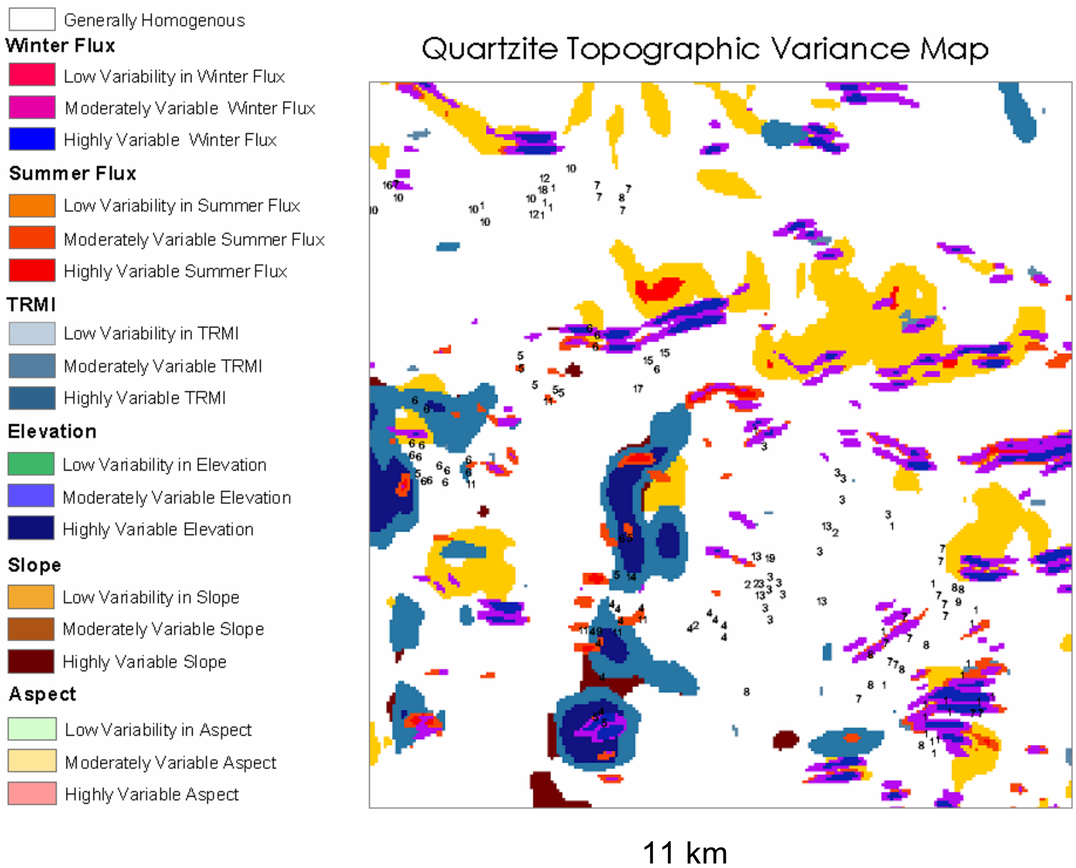


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Figure C4. Map of topographic and physiographic variability for Quartzite

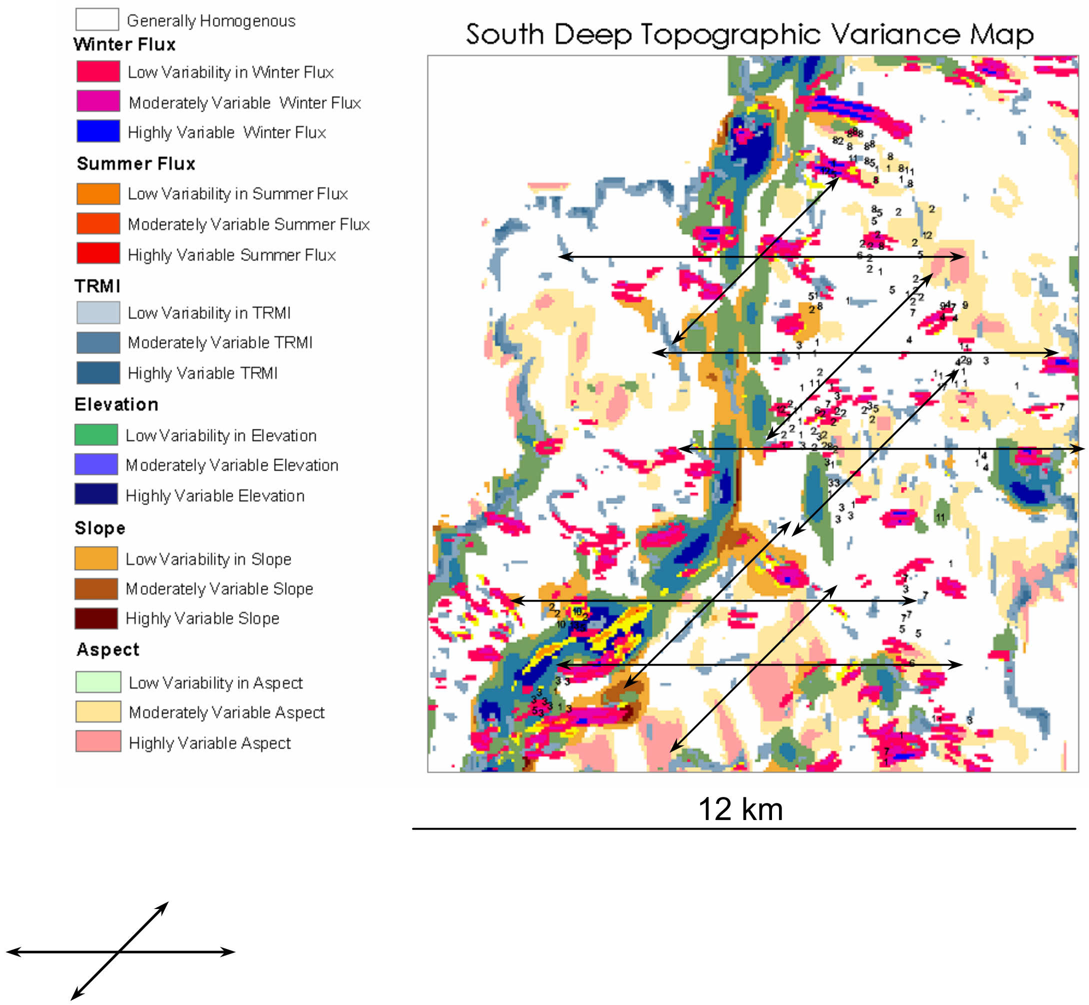
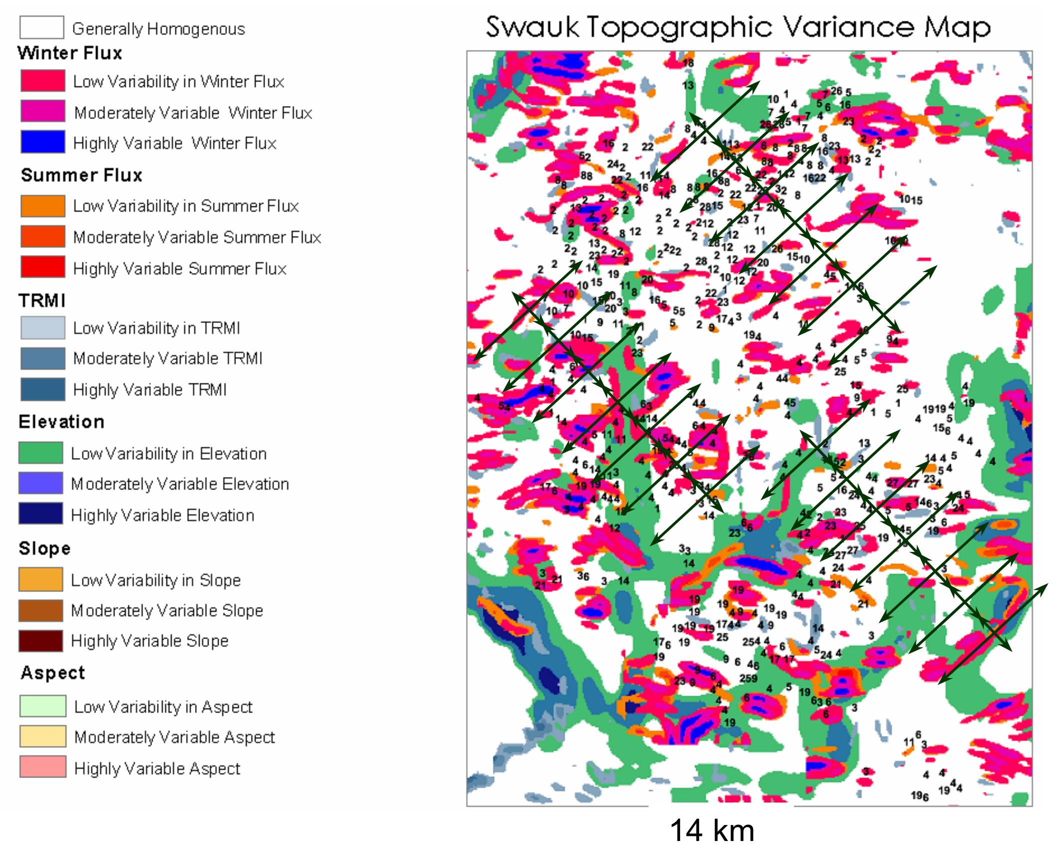
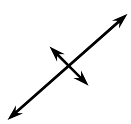


Figure C5 Map of topographic and physiographic variability for the South Deep with semivariogram model measurements of anisotropy for MFRI imposed on landscape.





Range of major axis (364m) in the SWNE direction and the range of the minor axis (171m) in the NWSE direction.

Figure C6 Map of topographic and physiographic variability for the Swauk with semivariogram model measurements of anisotropy for MFRI imposed on landscape.